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A funny thing happened on the way to articulation: N400 attenuation despite behavioral interference in picture naming

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ABSTRACT

We measured Event-Related Potentials (ERPs) and naming times to picture targets preceded by masked words (stimulus onset asynchrony: 80 ms) that shared one of three different types of relationship with the names of the pictures: (1) Identity related, in which the prime was the name of the picture ("socks" – <picture of socks>), (2) Phonemic Onset related, in which the initial segment of the prime was the same as the name of the picture ("log" – <picture of a leaf>), and (3) Semantically related in which the prime was a co-category exemplar and associated with the name of the picture ("cake" – <picture of a pie>). Each type of related picture target was contrasted with an Unrelated picture target, resulting in a 3 × 2 design that crossed Relationship Type between the word and the target picture (Identity, Phonemic Onset and Semantic) with Relatedness (Related and Unrelated). Modulation of the N400 component to related (versus unrelated) pictures was taken to reflect semantic processing at the interface between the picture's conceptual features and its lemma, while naming times reflected the end product of all stages of processing. Both attenuation of the N400 and shorter naming times were observed to pictures preceded by Identity related (versus Unrelated) words. No ERP effects within 600 ms, but shorter naming times, were observed to pictures preceded by Phonemic Onset related (versus Unrelated) words. An attenuated N400 (electrophysiological semantic priming) but longer naming times (behavioral semantic interference) were observed to pictures preceded by Semantically related (versus Unrelated) words. These dissociations between ERP modulation and naming times suggest that (a) phonemic onset priming occurred late, during encoding of the articulatory response, and (b) semantic behavioral interference was not driven by competition at the lemma level of representation, but rather occurred at a later stage of production.

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1. Introduction

"Look out for that car!" is a phrase that must be uttered very quickly to be useful to the listener. Luckily, from the moment an onlooker sees a car, they are able to identify it and name it in less than a second. To get from a Mercedes barreling down towards a hapless pedestrian and the utterance of the word, "car", we must access the relevant conceptual features ("vehicle, wheels, auto"), we must retrieve its interconnected amodal word-level representation "car" (the lemma), we must access its phonological word-form representation ("ka:r"), and we must select the phoneme representations which are necessary to prepare the appropriate articulatory gestures (Dell, Schwartz, Martin,

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Saffran, & Gagnon, 1997; Levelt, Roelofs, & Meyer, 1999).[1] It is still unclear, however, when each type of representation is activated and how activity at one level affects other levels during speech production. This study used a cross-representational masked priming paradigm in combination with both electrophysiological and behavioral measures to address these questions.

One widely accepted model of speech production argues that processing is largely serial and feed-forward (Levelt et al., 1999; Roelofs, 2004). According to this account, conceptual information interacts very closely with an amodal word-level representation, which serves as a link between conceptual and form information—the lemma. Importantly, according to Levelt, only one lemma is selected to advance to phonological encoding, without interference of activity from non-selected semantically related competitors. For example, when producing the word "dog", competition from semantically related items such as "cat" and "wolf" is only present at the stage of accessing its lemma, but has no influence on access to phonological or phonemic representations (Levelt et al., 1999; Roelofs, 2004). This feed-forward model can account for several experimental phenomena observed in picture naming studies in which participants are asked to name target pictures presented in close association with context words. These context words either match the target picture at different levels of representation (e.g. semantically, phonologically), or are unrelated to the picture. As discussed below, depending on the type of relationship shared between word and picture, both facilitation and interference effects on naming are observed.[2]

When presented with a context word that is identical to a target picture name ("cat" – <picture of a cat>), participants are typically able to name the picture faster than when the context word is unrelated to it (Glaser & Dungelhoff, 1984; Rosinski, 1977; Rosinski, Golinkoff, & Kukish, 1975; Smith & Magee, 1980). This behavioral facilitation effect is robust and is seen at a variety of Stimulus Onset Asynchronies (SOAs) (Biggs & Marmurek, 1990), and even when other items intervene between the context word and target picture (Durso & Johnson, 1979). According to Levelt's model, such facilitation arises through cross-representational identity priming because of close links between the comprehension system and the production system (Biggs & Marmurek, 1990; Monsell, Matthews, & Miller, 1992). Identity context words overlap with target picture names at multiple levels of representation: conceptual, lemma, phonological word-form and phonemes. This overlap means that activation from the context word primes the processing of the target picture name at multiple stages of processing, thereby facilitating its production (Levelt et al., 1999).

A similar facilitatory effect is sometimes observed when the context word is phonologically related to the target picture ("cap" – <picture of a cat>) (Ferrand, Grainger, & Segui, 1994; Lupker, 1982; Schriefers, Meyer, & Levelt, 1990). The degree of facilitation, however, depends on the extent and type of phonological overlap between the word and the picture (Ferrand, Segui, & Grainger, 1996; Ferrand et al., 1994). Relative to control conditions (such as unrelated words, nonsense strings, and audible noise), facilitation is usually seen when there is overlap between the context word (visual or auditory) and target picture, either in the onset phoneme or syllable ("board" – <picture of a bagel>) or the final syllable ("breaker" – <picture of an anchor>) (Schiller, 2008; Schriefers et al., 1990). Overlapping final phonemes, however, do not produce facilitation ("bald" – <picture of a sword>) (Schiller, 2004). The facilitation of picture naming by context words with overlapping phonemic onsets is termed the Onset Priming effect. It is reliably seen when the context word is masked, where it has been termed the Masked Onset Priming Effect or MOPE. This effect is also observed when targets are words and non-words (Ferrand et al., 1996; Forster & Davis, 1991). Facilitation on words is not observed, however, when the task is lexical decision rather than articulation (Ferrand et al., 1996; Grainger & Ferrand, 1996). Thus, the MOPE is usually explained by positing that overlap between the phonemic segment of the prime and the name of the target occur at a relatively late stage of preparation of an articulatory response (Grainger & Ferrand, 1996; Kinoshita, 2000; Schiller, 2008), after access to the conceptual, lemma or phonological word-form representations of the target.

In contrast to the facilitation effects described above, the presence of a context word which is semantically related (versus unrelated) to the target picture can, at least under some circumstances, lead to longer naming times to that target – a phenomenon known as the picture–word semantic interference effect (Lupker, 1979; Rosinski, 1977). Semantic interference is observed when a word is presented simultaneously with the target picture (0 ms SOA) as well as when it is presented immediately before (−160 ms SOA), or immediately after (+200 ms SOA) the target (Bloem, van den Boogaard, & La Heij, 2004; Mahon, Costa, Peterson, Vargas, & Caramazza, 2007). It can also be seen, under some circumstances, when the context word disappears with the onset of the picture, i.e. in a priming paradigm (Alario et al., 2000). According to Levelt's model of speech production, the picture–word semantic interference effect arises because of competition at a stage of word-level semantic processing, i.e. at the interface between the conceptual and

[1] Both lemma and phonological word-form representations can be considered 'lexical' in that they mediate between semantics and phonemes. Not all production models, however, acknowledge both these levels of representation. Levelt et al. (1999) and Dell et al. (1997) discuss the lemma level, while Caramazza (1997) refers to a modality-specific phonological word-form or lexeme representation (see also Starreveld & La Heij, 1996). In this study, we find it useful to refer to both lemma and phonological word-form representations when interpreting our findings in relation to previous studies (cf Fig. 1, Cutting & Ferreira, 1999), but we recognize that it is possible to adopt a more generic model, with the debate being the degree to which a generic lexical level of representation is influenced by activity at the phonemic level (e.g. Goldrick & Rapp, 2002).

[2] Many studies use the so-called picture–word interference paradigm in which a to-be-named picture is presented at the same time as the context word (the distractor). Other studies have used a priming paradigm in which the to-be-named picture is preceded by the context word (the prime). However, since distractor words can also appear before picture stimuli in the picture–word interference paradigm (i.e., a negative SOA), the only clear distinction between the two approaches is that word stimuli are removed before picture onset in the priming paradigm. Given the similarity in the two paradigms and the obtained results (e.g. Alario, Segui, & Ferrand, 2000), they will be presented together.

lemma levels of representation, which are closely connected through bidirectional spreading activation. The lemma of a conceptually related word will receive activation not only from its own presentation but also from the conceptual representation of the picture. This additional activation will slow down target lemma selection because of lateral inhibition among coactive lemmas (e.g. Cutting & Ferreira, 1999) or because of a choice-ratio selection threshold (Roelofs, 2004). After this, processing is serial in nature: phonological encoding only proceeds once such competing activation of lemmas is resolved (Levelt et al., 1999; Roelofs, 2004).

It is now apparent, however, that the semantic interference effect does not occur under all circumstances. This poses some challenges to the idea that selection occurs at the interface between the conceptual and lemma levels of representation, and indeed to serial models of speech production. First, the prototypical semantic interference effect is seen when the context word shares a categorical relationship with the target picture (''banana'' – <picture of a pear>) (La Heij et al., 1990). However, when the context word is also associatively related to the target picture (e.g. ''apple'' – <picture of a pear>), no interference is seen at an SOA of 0 ms (although it is seen when the word is presented very quickly afterwards at an SOA of + 75 ms (La Heij, Dirkx, & Kramer, 1990; see Alario et al., 2000, for a similar dissociation between effects to purely categorically related pairs, e.g. ''boat'' – <train>, and purely associatively related pairs, e.g. ''nest'' – <picture of a bird>, using a priming paradigm). Additionally, others have observed a facilitation, rather than interference, of naming times to pictures of objects presented with words that denote parts of such objects, e.g. ''engine'' – <picture of a car> (Costa, Alario, & Caramazza, 2005). These observations are hard to explain through selection by competition at the lemma level. These types of associations occupy a similar semantic space and would presumably act in a competitive fashion, similar to co-category exemplars, during lemma selection.

Second, if the semantic interference effect was due to selection at the lemma level, then the strength of the semantic relationship between the context word and the target picture should affect naming times proportionately, with closer semantic relationships resulting in more interference, leading to longer naming latencies. However the opposite has been observed: closer semantic relationships between context words and targets result in shorter naming times to the target (Mahon et al., 2007).

Third, selection by competition at the lemma level would predict that high frequency competitors would interfere more than low frequency competitors, as the resting activation of words is related to their frequency. In fact, the opposite has been observed: the naming times to pictures presented with low frequency context words are *longer* than to pictures presented with high frequency context words (Miozzo & Caramazza, 2003).

Finally, if selection occurred by competition at the lemma level, the semantic interference effect should still occur under subliminal masked priming conditions. However, a study by Finkbeiner and Caramazza (2006) showed that a subliminal masking procedure actually reversed the direction of the semantic interference effect. In that study, the prime word appeared for 53 ms, immediately followed by a backward mask, which was superimposed on the target picture. Rather than observing an interference effect on semantically related versus unrelated target pictures, the investigators reported a facilitation (priming) effect.

These types of observations have led to proposals that the picture–word semantic interference effect is driven by competition from semantically related distractors arising at a stage past the lemma selection. One possibility is that it occurs at the level of selecting phonological word-form representations (Starreveld & La Heij, 1996). Another is that it occurs still later during the selection of the articulatory response (Caramazza & Costa, 2000). This latter idea is referred to as the ''response exclusion'' hypothesis by Mahon et al. (2007), and draws analogies to the mechanism of interference seen in the classic Stroop paradigm (Lupker, 1979; Posner & Snyder, 1975; Rosinski, 1977; Stroop, 1935), in which interference is seen when a highly salient dimension of a stimulus is automatically processed but this conflicts or competes with a second dimension that is relevant to the required response. According to the response exclusion hypothesis, the semantic interference effect occurs because an articulatory response is automatically prepared on the basis of information extracted from context (distractor) words, and these alternative responses must be removed before the appropriate target-driven response can be generated. Most importantly, according to this hypothesis, it is harder to exclude semantically related distractors than unrelated distractors as potential responses for the picture target.

If the picture–word interference effect can be attributed to competition that occurs past the stage of lemma selection, i.e. past the stage of word-level semantic processing, this implies that there is no principled distinction between a cross-modal word–picture semantic priming paradigm, and a picture–word semantic interference paradigm. Whether a semantically related context word will facilitate or interfere with picture naming will depend on the type of semantic relationship between the context word and the target picture, and the precise combination of experimental parameters. At a short SOA, a semantically related word prime will automatically facilitate word-level semantic processing of a target picture. However, such facilitation will be outweighed by competition at later stages of production, and the end result is interference on naming times. A word that is semantically associated but that does not share a categorical relationship with a target picture poses no competition at late stages of production and will not lead to interference; rather, it will facilitate processing, leading to faster naming times. A low frequency semantically related competitor word might lead to interference on naming times at a later stage of response selection (Miozzo & Caramazza, 2003).

Finally, when the context word is not available at all for later stages of processing, whole-word semantic priming is longer outweighed and naming times are facilitated. This is how Finkbeiner and Caramazza (2006) explained the reversal of reaction times in their subliminal masking study: full masking of the context word meant that it was unavailable as a response alternative and could not interfere with response selection during articulation.

However, its semantic features still automatically primed the conceptual and/or lemma representation of the target picture, leading to facilitation on naming times.

Attributing the picture–word interference effect to semantic competition occurring past the stage of lemma selection has theoretical implications for models of speech production. As discussed above, the serial production model put forward by Levelt and colleagues is strictly feed-forward and argues against interactivity past selection of the lemma: one lemma must be selected before proceeding to the next stage (Levelt et al., 1999; Roelofs, 2004). The experimental phenomenon of semantic interference has been used to support the theoretical assumptions of Levelt's model: conceptual features are used to select a lemma, but they do not permeate to stages of phonological encoding or articulatory preparation. If, however, the phenomena of picture–word interference are better accounted for by competition at a later stage of processing, then this implies more interactivity and parallel processing during speech production (Dell et al., 1997; Goldrick & Rapp, 2002). The debate, however, is far from resolved. Proponents of Levelt's model have argued that additional mechanisms, such as self-monitoring may explain the semantic-distance and frequency effects on picture naming mentioned above (Roelofs, 2004).

1.1. Event-related potentials

One of the difficulties in distinguishing between these different accounts and, more generally, in interpreting naming times of pictures, is that naming times reflect the culmination of multiple stages of processing. This makes it difficult to identify the locus of any effect of a context word on naming. For example, the facilitation of naming times to a picture presented with an identical context word could be due to facilitated access to its conceptual features, its lemma, its phonological word-form representation, and/or its phonemic representations. Indeed, as discussed above, if the picture–word interference effect cannot be explained by selection at the lemma level during a stage of word-level semantic processing, a semantically related context word might prime a target picture, facilitating access to its lemma representation, but interfere with subsequent stage(s) of processing.

The interpretation of picture naming time effects would therefore be complemented by the addition of a temporally precise method that can measure activity during multiple processing stages prior to production. Event-Related Potentials (ERPs) provide such temporal acuity. Electrical activity at the surface of the scalp can be measured throughout an experiment and time-locked to specific events, such as the presentation of target pictures. Activity is averaged across similar trials across subjects, and the timing, morphology and amplitude of the resulting grand-average waveform can yield insights into the underlying neural processes.

A long history of ERP research has identified several components that are associated with the processing of both words and pictures. One component that is consistently modulated by manipulations of semantic content is the N400, a negative-going waveform peaking at approximately 400 ms post-stimulus onset (Kutas & Hillyard, 1980). The amplitude of the N400 is large when the target stimulus is presented without any context. It is attenuated (less negative) when a target word is preceded by a congruous context. For example, target words preceded by identical or semantically related words show a smaller N400 than those that are preceded by unrelated words (Bentin, McCarthy, & Wood, 1985; Rugg, 1985). The N400 to words can also be modulated by various lexical factors including word frequency (Rugg, 1990; Van Petten & Kutas, 1990) and neighborhood size (Holcomb, Grainger, & O'Rourke, 2002). The attenuation of the N400 to a word target preceded by a semantically related context is thought to reflect reduced semantic processing of that word because its amodal lexical representation is pre-activated by the context (Kutas & Federmeier, 2011). Importantly, N400 modulation is not dependent on a behavioral response. It is, in fact, possible to see an attenuation of the N400 to words in the presence of behavioral inhibition (Holcomb, Grainger, & O'Rourke, 2002).

Pictures also evoke an N400 and, like the N400 evoked by words, this is also modulated by semantic context (Barrett & Rugg, 1990; McPherson & Holcomb, 1999). For example, the N400 evoked by a picture is attenuated when that picture is preceded by a semantically related picture (Barrett & Rugg, 1990; McPherson & Holcomb, 1999) or word (Johnson, Paivio, & Clark, 1996). However, unlike to words, the N400 to pictures is sometimes preceded by a slightly earlier frontally-distributed component, called the N300 (Barrett & Rugg, 1990; McPherson & Holcomb, 1999). This N300 is thought to reflect access to the structural semantic features that are specific to visual objects. It is thought to be distinct from an earlier N/P190 component that may index activation of a picture's perceptual features (Eddy, Schmid, & Holcomb, 2006, Eddy & Holcomb, 2010). It can also be distinguished from the N400 itself which is usually interpreted as reflecting semantic processing that occurs at the interface between the conceptual features and a more abstract, amodal level of representation.

Traditionally, ERPs have mainly been used to examine mechanisms of language comprehension rather than production. This is because articulation causes substantial noise in the EEG signal, which can potentially render subtle cognitive effects of interest undetectable. Because of this, early ERP studies exploring production used the lateralized readiness potential – an index of response preparation – to explore the temporal sequence of retrieving different representations. These studies suggested that the picture's conceptual representation was accessed before its lexico-semantic representation, which in turn, was accessed before its phonological representation (e.g. Rodriguez-Fornells, Schmitt, Kutas, & Münte, 2002; Schmitt, Munte, & Kutas, 2000; Van Turennout, Hagoort, & Brown, 1997, 1998). However, because overt naming responses were delayed, and participants performed quite complex tasks (combining left–right button-presses with go/no-go decisions), conclusions about the precise timing of retrieving these different representations in natural language production were limited.

Another approach was taken by Jescheniak, Schriefers, Garrett, and Friederici (2002) who measured ERPs to

auditory probe words that were presented 550 ms after the onset of a picture. Participants named the picture, but only when cued to do so, 1350 ms after its onset. A smaller (less negative) N400, from 400 to 800 ms, was seen to probe words that were semantically (categorically) related to the target picture compared with semantically unrelated probe words. This was interpreted as reflecting semantic priming of the word by the picture's conceptual or lemma representation. Importantly, a similar pattern and time-course of N400 modulation was observed when, rather than name the pictures, participants made semantic (size) judgments about them. This suggests that access to the conceptual and/or lemma representation of a picture during a naming task, i.e. word-level semantic processing, is not qualitatively different from access to these representations during a semantic decision task. This is consistent with the idea that these levels, and this stage of word-level semantic processing, is shared between comprehension and production systems (Levelt et al., 1999). When the probe word was phonologically related to the target picture (sharing an initial consonant–vowel segment), modulation within the N400 time window was still seen to the probe word in the naming task. This suggested that the phonological word-form representation of the picture's name was available, and that this facilitated word-level semantic processing, through feedback, modulating the N400. However, no such phonological effect on the N400 was seen in the semantic decision task, suggesting that participants did not automatically access the phonological code of the picture unless it was selected for production. This interpretation was further supported by a follow-up study in which ERPs were measured to probe words that were phonologically related to semantic associates of the to-be-named picture (e.g. "goal" which is phonologically related to "goat", which is semantically related to the target picture <sheep>). No N400 modulation was seen to these probes, again suggesting that only the phonological representation of the name of the picture – not of its lexico-semantic associates – was activated (Jescheniak, Hahne, & Schriefers, 2003).

These studies established that, while a similar stage of whole-word semantic processing may be shared across semantic processing and production tasks, phonological word-form representations are more likely to be activated during production tasks than in purely semantic processing tasks (see also Vihla, Laine, & Salmelin, 2006 for converging evidence). However, because the probe words were introduced so much later than the onset of the picture, they do not shed light on exactly when after picture onset these representations became available.

Recently, several investigators have found that it is in fact possible to obtain accurate waveforms time-locked to target pictures, even when participants are asked to overtly name the picture (see Ganushchak, Christoffels, and Schiller (2011), for a review). This is because the onset of articulation typically occurs after the onset of components of interest. Three recent ERP studies exploited this and measured ERPs as participants named pictures that were either low or high frequency: Laganaro et al. (2009) reported divergence in the waveform beginning at around 270 ms after picture onset, while Strijkers, Costa, and Thierry (2009) and Strijkers, Holcomb, and Costa (2011) showed an even earlier divergence between 150 and 200 ms (on the P2 waveform). Strijkers et al. (2009) also reported a similar early divergence when Spanish–Catalan bilingual participants named pictures that shared or did not share phonological features across the two languages (cognates versus non-cognates). In another study (Costa, Strijkers, Martin, & Thierry, 2009), participants named pictures from a set of intermixed semantic categories (e.g., turtle, hammer, tree, crocodile, bus, axe, snake, etc.) and ERPs were measured to pictures from a given semantic category that appeared either earlier in the set (e.g. crocodile) or later in the set (e.g., snake). The ERP waveforms diverged at approximately 200 ms – a finding that was consistent with an earlier MEG study by Maess, Friederici, Damian, Meyer, and Levelt (2002) who reported a similar early effect to pictures appearing within an intermixed versus homogeneous semantic category set.

These studies are important in that they suggest that, during production, access to some linguistic information can begin as early as 200 ms after picture onset, perhaps because the intention to speak produces top-down activity, which facilitates early access to such representations (Strijkers et al., 2011). However, it should be noted that the focus of these studies was on the timing of the initial divergence in the ERP waveforms as an indicator for when naming-relevant information first became available during production. As argued elsewhere (e.g., Grainger & Holcomb, 2009), when interpreting ERP results, one must draw a distinction between estimates of the onset of a given effect, determined by the fastest feedforward processes, and the bulk of the effect that likely reflects the consolidation of processing as information accrues in the representations that are driving the effect, plus possibly the stabilization of information transfer between different levels of representation (meaning and form, for example). In other words, evidence for access to linguistic information at around 200 ms post-picture onset is not incompatible with the observation that semantic or lexical variables can modulate the N400 ERP component during production tasks.

Two previous studies speak directly to how the N400 is modulated to pictures during production. First, Chauncey, Holcomb, and Grainger (2009) recorded ERPs while participants named picture targets that were preceded by word primes (presented for 70 ms followed by a 50 ms mask) that corresponded either to the name of the picture target or to an unrelated picture name. Clear modulation was seen within the 300–500 ms N400 time window, with a less negative N400 to pictures preceded by identity than non-identity words. A very similar attenuation of the N400 was seen in a second experiment when bilingual participants named the picture target in their second language (the word prime appeared in their first language). The cross-language N400 priming effect was interpreted as reflecting facilitation of the picture's amodal semantic representation (distinct from its phonological word-form representation, since only non-cognate translation equivalents were tested).

In a second study using a long-lag primed naming paradigm, Koester and Schiller (2008) reported a smaller

(less negative) N400 between 350 and 650 ms to pictures that were preceded by transparently morphologically related compound words, than to pictures preceded by unrelated words. The same degree of N400 modulation was seen to pictures preceded by opaquely morphologically related compound words. This suggests that, rather than only reflecting cross-modal priming of the picture's conceptual features, N400 modulation during production reflected at least some priming of a more abstract word-level representation of the picture by the word's decomposed morphemes.[3] No ERP modulation was seen to picture targets preceded by words that were only phonologically related (versus unrelated) to the target's name.[4]

In both these production studies, the N400 effect evoked by primed (versus unprimed) pictures was similar in timing and morphology to the N400 seen to primed (versus unprimed) pictures and words using word comprehension tasks. Thus, taken together, they suggest that, just as in comprehension tasks, the N400 evoked by pictures in naming tasks reflects activity at the interface between conceptual features and a more abstract word-level representation (the lemma).

1.2. The current study

The current study sought to examine the time-course of facilitation and interference during an overt picture-naming task by measuring both ERPs and naming latencies. We created three sets of word–picture pairs with Identity, Phonemic Onset and Semantic relationships (see Fig. 1). In the Identity pairs, the word was the name of the picture (e.g. socks – <picture of socks>). In the Phonemic Onset related pairs, the word had the same initial segment as the picture name (e.g. log – <picture of a leaf>). In the Semantically related pairs, the word was both categorically related and associated with the picture name (e.g. cake – <picture of a pie>). We compared each related word–picture pair with an unrelated pair (e.g. waffle – <picture of socks>; chalk – <picture of a leaf>; hurricane – <picture of a pie>). For each Relationship Type, target pictures were counterbalanced across two lists (seen by different participants). This meant that, for each Relationship Type, a given target picture appeared in the related condition in one list and the unrelated condition in another list (see Methods for further details), and that no individual saw the same target picture more than once or in more than one condition.

In all trials, the words appeared for 60 ms and were followed by a backward mask of 20 ms (SOA 80 ms) before the target picture appeared. This combination of SOA and mask duration ensured that processing of the words was not completely subliminal (we presented 10 word–picture pairs, using the same parameters, to all participants after the study, as well as to 11 participants who did not take part in the study, and asked them to name the word: on average, 7/10 were correctly named). This meant that the representation of the word was still likely to have been available during the response stage of naming the picture. On the other hand, the short SOA, with some masking of the context word, ensured that any priming effect of the word on the picture would reflect automatic activity rather than controlled post-lexical strategies. The use of a short mask also ensured that the words were all processed to the same degree, avoiding potential problems of non-uniform masking by different pictures with different physical properties. Unlike classical picture–word interference studies, the context word disappeared with the onset of the target picture. This was important to ensure that ERPs were measured to an identical stimulus across the related and unrelated conditions (otherwise any modulation in ERPs could be attributed to low-level differences across these conditions).

We made the following predictions regarding the pattern of ERP modulation and picture naming latencies. First, we expected that the amplitude of the N400 would be attenuated and naming times would be shorter to picture targets preceded by words that were identical (versus unrelated) to the picture's name. This would replicate previous findings of behavioral (Rosinski et al., 1975) and ERP (Chauncey et al., 2009) identity priming during picture naming, and would indicate facilitation by overlapping activation from the prime word at multiple levels of representation – conceptual, lemma and phonological.

Second, based on previously reported behavioral findings (Schiller, 2004, 2008), we predicted that pictures preceded by prime words with the same phonemic onset as the target picture names would be named faster than target pictures preceded by unrelated words. It was somewhat unclear whether or when we would see a signature of such facilitated processing in the ERP waveform. If we observed any ERP modulation on the N400 component, this would suggest feedback from the activated phonemic representations of the target picture to activity at the conceptual/lemma interface (Dell et al., 1997). Otherwise, any behavioral effects would be attributable to priming occurring at a later stage of preparation of the articulatory response (Grainger & Ferrand, 1996; Kinoshita, 2000; Schiller, 2008).

Of most interest was the pattern of ERPs and naming times to the picture targets preceded by semantically related words. As noted above, our SOA of 80 ms between word and picture is well within the range at which

[3] We are not arguing that N400 priming in Koester and Schiller's study occurred purely at a level of morphological representation that was devoid of any semantic information. In fact, many of the opaquely morphologically related compound primes did share some conceptual relationship with the target (although not nearly to the same degree as the transparent morphologically related primes, Koester and Schiller, personal communication). Our main point is that, given that the magnitude of N400 effect was the same size to targets preceded by transparently morphologically related and opaquely morphologically related compound words (each relative to unrelated targets), these findings suggest that N400 modulation during picture naming is not driven entirely by access to a picture's conceptual features, but also by access to some more abstract lexical representation.

[4] In another recent study using the classic picture–word interference task, Dell'Acqua et al. (2010) reported a less negative waveform between 250–450 ms to picture targets with superimposed distractor words which were categorically related versus unrelated to the picture's name (but see Hirschfeld, Jansma, Itea, & Zwitserlood, 2008, who reported no effect to a similar manipulation). The authors suggested that this ERP modulation reflected processing at the lexical level prior to phonological encoding, although they did not identify it as N400 priming. A similar pattern of ERP modulation was observed when the superimposed distractor words shared the first two or three phonemes with the picture's name. This was interpreted as reflecting facilitated phonological access, which impacted lexical processing.

Word-Picture Relationship		Context Word	Picture Target	Length	# Phonemes	# Syllables	Log Freq.
Identity							
	Related	socks		5.8 (2.0)	4.7 (1.6)	1.7 (0.7)	8.1 (1.5)
	Unrelated	waffle					
Phonemic Onset							
	Related	log		6.0 (1.7)	4.8 (1.5)	1.8 (0.7)	8.2 (1.6)
	Unrelated	chalk					
Semantic							
	Related	cake		5.7 (1.8)	4.7 (1.5)	1.7 (0.7)	8.0 (1.3)
	Unrelated	hurricane					

Fig. 1. Example of word–picture stimuli pairs. Stimuli consisted of a context word matched to a target picture on one of three types of relationships: Identity, Phonemic Onset, or Semantic. For each Relationship Type, an Unrelated context word was paired with the same picture. Counterbalancing was within Relationship Type across two experimental lists (to be seen by different participants). For example, a <picture of socks> might be preceded by the word 'socks' in list 1 (Identity related) but by the word 'waffle' in list 2 (Unrelated). The <picture of a leaf> might appear with the word 'log' in list 1 (Phonemic Onset related) but with the word 'chalk' (Unrelated) in list 2. The <picture of a pie> might appear with the word 'cake' in list 2 (Semantically related), but with the word 'hurricane' in list 1 (Unrelated). Thus, no individual participant saw a given target more than once, but across all participants, the same target picture for a given Relationship Type was seen in both the related condition and the unrelated condition. The average length, number of phonemes, number of syllables, and frequencies of the names of the target pictures are given, with standard deviations in parentheses. Values were taken from the English Lexicon Project, http://elexicon.wustl.edu/. The pictures were presented in color and were taken from the Hemera Photo Objects database (Hemera Technologies Inc, 2002).

behavioral semantic interference has been previously reported (Bloem et al., 2004; Mahon et al., 2007). Importantly, as discussed above, the 20 ms backward mask did not eliminate awareness of the word or reduce its availability as a response alternative during selection, distinguishing our parameters from those used by Finkbeiner and Caramazza (2006) who used a 53 ms SOA with complete masking of the picture, and who observed facilitation on naming times. We therefore expected to see a semantic interference effect on naming times, i.e. we expected naming times of picture targets preceded by semantically related words to be longer than those preceded by semantically unrelated words.

The question we asked was whether this behavioral pattern of interference would pattern with or dissociate from the modulation of the N400. This would help identify the locus of the behavioral semantic interference effect. As discussed above, we take the N400 to be an index of neural activation at the interface between the conceptual and lemma levels of representation, occurring at a stage of word-level semantic processing that is shared between comprehension and production systems. If the pattern of N400 modulation mirrored the pattern of behavioral interference, with a larger (more negative) N400 to target pictures preceded by semantically related than unrelated words, this would provide strong evidence for selection by competition at the conceptual–lemma interface, as suggested by Levelt et al. (1999). If, on the other hand, the N400 to pictures preceded by semantically related (versus unrelated) words was attenuated, this would suggest that the lemma representation of the picture had been automatically primed by the context word. This would, in turn, suggest that any semantic interference on naming times occurred past the lemma stage of processing, implying feedforward activity from the semantic to later stages of processing during production (Caramazza, 1997; Dell et al., 1997; Goldrick & Rapp, 2002).

2. Methods

2.1. Design and stimuli

A set of 330 color images was taken from the Hemera Photo Objects database (Hemera Technologies Inc., 2002). These images included depictions of household items, animals, food items, and other easily recognizable objects. All pictures were cropped and resized to fit a 256 × 256 pixel image with a white background. In order to determine which of these pictures were given consistent names, an independent norming study was carried out in which a group of 24 undergraduate participants were asked to identify the pictures with a single name. Two-hundred-and-seventy pictures, which were consistently named by at least 70% of participants, were selected as targets.

Each image in this set of 270 pictures was paired with a context word (always a noun) to construct word–picture pairs that had one of three types of relationship: Identity related, Semantically related and Phonemic Onset related. Ninety related pairs were constructed for each relationship. An example of each type of relationship is given in Fig. 1, and the full set of related pairs can be found at http://www.nmr.mgh.harvard.edu/kuperberglab/materials.htm.

Identity related pairs consisted of a context word that corresponded to the name of the picture, e.g. socks – <picture of socks>. Semantically related pairs consisted of context words and target pictures that were both associated and co-category exemplars (Van Overschelde, Rawson, &

Dunlosky, 2004), e.g. cake – <picture of a pie>. Association was determined by selecting context words that elicited the name of the target picture during free association, as indexed using the Florida Free Association Norms database (Nelson, McEvoy, & Schreiber, 2004). Prime words were at least the third most common associate of the target word, with a mean association value of 0.17. In addition, Latent Semantic Analysis (LSA) (Landauer & Dumais, 1997) was used to confirm semantic relatedness between primes and target words. We obtained pairwise comparison values for primes and targets using the LSA database available at www.lsa.colorado.edu. All semantically related word–picture pairs had a minimum correlation value of 0.10 ($M = 0.422$, SD = 0.193).

The Phonemic Onset related pairs consisted of context words that had the same initial phonological segment as the target picture name, but not the same initial syllable (e.g. log – <picture of a leaf>). If the name of the picture began with a consonant–consonant compound before its initial vowel, a context word with the same compound was selected (e.g. sparrow – <picture of a spider>). If the name of the target began with a vowel, then a context word beginning with a vowel of the same phonology was used (e.g. orchid – <picture of an orange>). Sixteen out of the 90 Phonemic Onset related word–picture pairs had overlap on the first vowel, but this overlap was orthographic only – not phonological (e.g. canoe – <picture of a cat>), as verified using norms from the English Lexicon Project http://elexicon.wustl.edu/. All primes were concrete words.

For each Relationship Type (Identity related, Phonemic Onset related and Semantically related), Unrelated pairs were created by pseudo-randomly pairing the picture targets with word from another target picture. This resulted in a 3×2 design that crossed Relationship Type between the context word and the target picture (Identity, Phonemic Onset and Semantic) by Relatedness (Related and Unrelated). There was no significant difference in log frequency ($F(2,178) = 1.558$, $p > 0.217$), number of letters ($F(2,178) = .582$, $p > 0.550$), number of phonemes ($F(2,178) = 0.182$, $p > 0.830$), or number of syllables ($F(2,178) = 0.848$, $p > 0.424$) of the names of target pictures across the three Relationship Types (see Fig. 1; values taken from English Lexicon Project http://elexicon.wustl.edu/). The pictures were also matched across the three Relationship Types on familiarity (values taken from the MRC Database and available for 66% of the targets used, $F(2,176) = 1.252$, $p > 0.287$).

These word–picture sets were then pseudo-randomly counterbalanced, within Relationship Type, across two experimental lists (to be seen by different participants). For example, referring to Fig. 1, a <picture of socks> might be preceded by the word 'socks' in list 1 (Identity related) but by the word 'waffle' in list 2 (Unrelated). The <picture of a leaf> might appear with the word 'log' in list 1 (Phonemic Onset related) but with the word 'chalk' (Unrelated) in list 2. And the <picture of a pie> might appear with the word 'cake' in list 2 (Semantically related), but with the word 'hurricane' in list 1 (Unrelated). Thus, each list constituted 270 word–picture pairs: 45 Identity related, 45 Phonemic Onset related, 45 Semantically related and 135 Unrelated pairs. This meant that no individual saw the same target more than once, but across all participants, the same target picture for a given Relationship Type was seen in both the related condition and the unrelated condition.

2.2. ERP experiment

2.2.1. Participants

Twenty-one Tufts students (age 18–27; 8 males) initially participated. Individuals with histories of psychiatric or neurological disorders, who had learned languages other than English before age 5, or who were left-handed according to the modified Edinburgh handedness inventory (Oldfield, 1971), were excluded. Each participant gave written informed consent in accordance with the procedures of the Institutional Review Board of Tufts University and was paid for participation.

2.2.2. Stimulus presentation and EEG recording

Participants were randomly assigned to one of the two lists used for counterbalancing. They sat in a comfortable chair in a dimly lit room separate from the experimenter and computers. They were given a practice block of 10 novel items prior to the experiment. Note that, unlike some previous studies of picture naming, we did not familiarize participants with the names of the pictures used in the experiment itself. This was in order to avoid potential repetition priming and episodic memory effects that can influence both the N400 and the late positivity ERP components, and which could potentially have interacted with the variables of interest and/or reduced our power to detect effects. Also familiarization would have likely reduced picture naming latencies inducing articulation artifact into the ERPs at an earlier point in time, thus restricting the latency range for observing ERP effects.

All words appeared in white Arial font against a black background on a 19-in. CRT monitor, which was placed level with participants' gaze as they sat in a chair approximately 60 in. away. On each trial a fixation prompt appeared for 500 ms followed by a forward mask ("##########") for 200 ms, the context word for 60 ms, then a backward mask of random consonants ("BKJRLWVS") for 20 ms, followed by the target picture which remained on the screen for two seconds or until it was named. The timing of a typical trial is depicted in Fig. 2. Participants were instructed to name the pictures as quickly and accurately as possible. Their responses were recorded with in-house software that began recording as soon as the target picture appeared. A blank screen was presented between trials for a variable inter-trial interval between 1500 and 2500 ms during which participants could blink to avoid artifact during trials. Participants were given breaks every 15 trials during which they were told they could move freely.

Twenty-nine tin electrodes recorded the electroencephalogram (EEG) and were held in place on the scalp by an elastic cap (Electro-Cap International, Eaton, OH). Electrodes were placed in standard International 10–20 System locations as well as 10 additional sites situated primarily between frontal and central sites and between central and parietal sites (see Fig. 3). Electrodes were also placed below

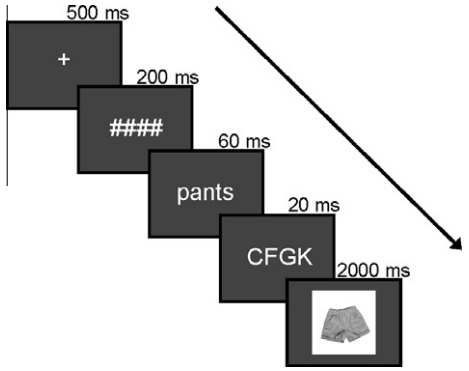

Fig. 2. Example trial. Each trial consisted of a fixation prompt, a forward mask, the context word, a backward mask of random consonants and the target picture, in that order.

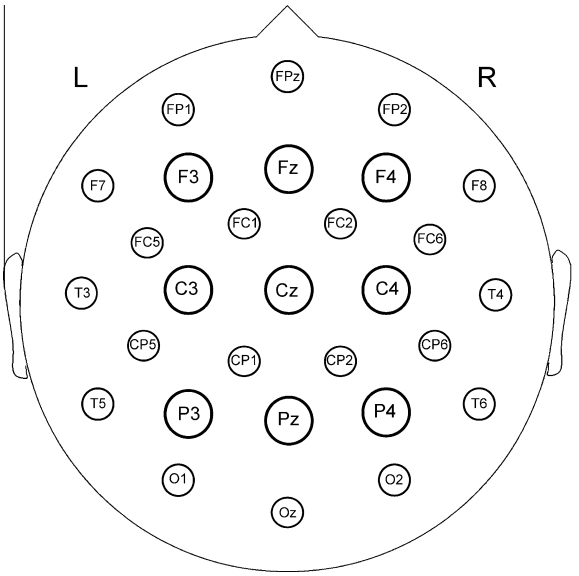

Fig. 3. EEG recording array. The sites used for recording EEG were the standard International 10–20 System locations as well as 8 additional sites. Larger circles indicate the nine sites used for analysis.

the left eye and at the outer canthus of the right eye to monitor vertical and horizontal eye movements. The EEG signal was amplified by an Isolated Bioelectric Amplifier System Model H&W-32/BA (SA Instrumentation, San Diego, CA) with a bandpass of 0.01–40 Hz and was continuously sampled at 200 Hz by an analogue-to-digital converter.

2.2.3. Behavioral data analysis

We excluded one participant from the behavioral analysis because his naming time data were missing due to technical problems. For all other participants, we analyzed their median naming latencies on correctly answered trials in each condition. Outliers (responses exceeding two standard deviations above the mean of that participant's median reaction time across all conditions) were excluded from analyses. The use of median naming times as a central tendency parameter is appropriate in a dataset like this one where the range in naming times across participants was large in comparison with the average differences between conditions in individual participants, see Ratcliff (1993). Naming time data were analyzed with ANOVAs. In a subjects analysis, we used median naming times across all correctly-answered items within each condition; within-participant factors were Relationship Type (Identity, Phonemic Onset and Semantic) and word–picture Relatedness (Related versus Unrelated). In an items analysis, we took the median naming times to each target picture, across the participants who correctly named that picture; Relationship Type was a between-items factor and Relatedness was a within-items factor.

2.2.4. ERP data analysis

ERPs were averaged off-line at each electrode site for each experimental condition using a −50 to +50 ms peristimulus baseline and lasting until 1170 ms post-picture onset. Across all participants, the lowest value in the range of median naming times was 653 ms (see Fig. 4B for full ranges in each condition) and so, to avoid speech-related artifact, we only analyzed and show ERP activity up until 600 ms post-picture onset (in some participants, there were some individual trials with naming times less than 600 ms but these constituted less than 3% of all trials across all participants). Trials contaminated with eye artifact (detected using a polarity inversion test on the left

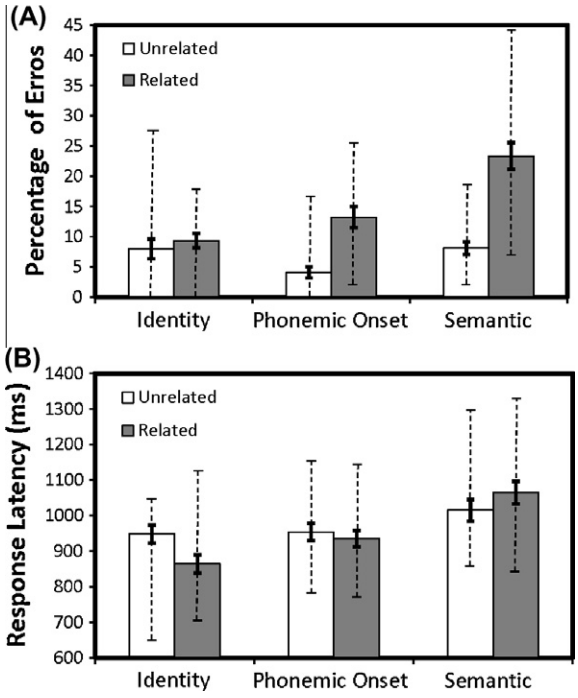

Fig. 4. Picture naming behavioral data. Bar graphs showing the mean percentage of errors (A) and the mean (across subjects) of the median naming times across items of a given condition (B) to pictures preceded by unrelated and related context words. The related pairs were either Identity related, Phonemic Onset related or Semantically related. Solid line error bars depict standard errors of these scores, and dotted line error bars depict the ranges (the maximum and minimum value across all participants for each condition).

eye channel) or amplifier blockage were excluded from analyses. One participant was excluded altogether from the ERP analysis because of a high artifact rejection rate. Across the remainder of the participants, artifact contamination from eye movement or amplifier blocking led to the rejection of 9.4% of trials and this did not differ across experimental conditions (no main effect of Relationship or Relatedness and no interaction between these two factors, all Fs < 2.60, all ps > 0.10).

ERP data from a representative sub-array of nine channels were used for analysis. This sub-array constituted three columns over left, center and right hemisphere locations, each with three electrode sites extending from the front to the back of the head (see Fig. 3). We have used a similar approach to analyze ERP data in a number of previous studies and find it to be a good compromise between simplicity of design (a single ANOVA can be used in each analysis epoch) and describing the overall distribution of effects. All data were analyzed using multi-factor repeated measures ANOVAs with within-participant factors of Relationship Type (Identity, Phonemic Onset, semantic), word–picture Relatedness (Related, Unrelated), Laterality (left, midline, right), and Anterior Posterior (AP) Distribution electrode placement (frontal, central, parietal). The dependent measures were the mean amplitude measurements in three consecutive time windows: 100–200 ms, 200–350 ms, and 350–550 ms post-stimulus onset. Previous work in our lab has used similar windows to assess activity of the N/P150, N250/N300 and N400 components (Eddy & Holcomb, 2010; Eddy et al., 2006). The window used to assess activity in the N400 epoch is also similar to that used in other picture naming studies (e.g. Koester & Schiller, 2008). In the reporting results of these repeated measures ANOVAs, we use the Huynh and Feldt (1976) correction.

We supplemented the analyses described above with a more post-hoc but finer-grained analysis in which we examined modulation across related and unrelated conditions for each Relationship Type at each sampling point (every 5 ms) until 600 ms after picture onset, using analyses of variance (ANOVAs) in multiple regions across the scalp, encompassing all electrode sites (see Kuperberg, Kreher, Swain, Goff, & Holt, 2011, Fig. 1). We noted intervals in which a sequence of at least 12 consecutive tests (Guthrie & Buchwald, 1991) in one or more regions showed a significant difference between conditions (at $p < 0.05$).

3. Results

3.1. Behavioral results

3.1.1. Accuracy

Error rates are shown for each condition in Fig. 4A. They were examined through a 2 × 3 repeated measures ANOVA, and showed a main effect of Relatedness ($F(1,19) = 104.53$, $p < 0.001$) due to more errors in the related than the unrelated conditions, and a main effect of Relationship Type ($F(2,38) = 27.78$, $p < 0.001$) due to significantly more errors in the Semantic than either the Identity ($t(19) = 5.35$, $p < .001$) or the Phonemic Onset ($t(19) = 5.27$, $p < .001$) conditions.

There was also a significant interaction between Relatedness and Relationship Type ($F(2,38) = 11.62$, $p < 0.001$). Follow-up t-tests at each level of Relationship Type showed significantly more errors on Related than on Unrelated targets in the Semantic condition ($t(19) = 7.389$, $p < .001$) and in the Phonemic Onset condition ($t(19) = 6.574$, $p < .001$), but not in the Identity condition ($t(19) = .659$, $p = .518$). Follow-up ANOVAs at each level of Relatedness showed significant differences between the three Relationship Types on the Related targets ($F(2,38) = 21.55$, $p < .001$), due to more errors on the Semantically related than either the Phonemic Onset related ($t(19) = 5.27$, $p < .001$) or the Identity related ($t(19) = 5.35$, $p < .001$) targets. In addition, there were significant effects of Relationship Type on the Unrelated targets ($F(2,38) = 6.41$, $p < .005$), due to more errors in naming the Semantically unrelated targets than the Phonemic Onset unrelated targets ($t(19) = 4.49$, $p < .001$), as well as more errors in naming the Identity unrelated targets than the Phonemic Onset unrelated targets ($t(19) = 2.72$, $p < .015$).

3.1.2. Naming times

The averages, standard errors and ranges of participants' median naming times for each correctly-named target picture in each condition are shown in Fig. 4B. These naming latencies are longer than in most picture naming studies, probably because all picture items were novel (as noted above, we did not practice participants on experimental items before the ERP experiment, and we counterbalanced lists so that no individual participant saw a given target in more than one condition). These median naming times were examined with 2 × 3 ANOVAs, both by subjects (Relatedness and Relationship Type were within-subjects variables) and by items (Relationship Type was a between-items variable and Relatedness a within-items variable).

There was a marginally significant effect of Relatedness in the subjects analysis ($F1(1,19) = 3.90$, $p = .063$) but not in the items analysis ($F2(1,265) = 2.06$, $p = .152$). There was also a main effect of Relationship Type ($F1(2,38) = 49.97$, $p < .001$; $F2(2,265) = 11.29$, $p < .001$). Of most interest, however, there was a significant interaction between Relationship Type and Relatedness ($F1(2,38) = 11.72$, $p < .001$; $F2(2,265) = 12.27$, $p < .001$). This was first followed up by examining the effect of Relatedness for each Relationship Type using paired t-tests. Identity related pictures were named significantly faster than Unrelated pictures ($t1(19) = 3.48$, $p < .005$; $t2(88) = 4.00$, $p < .001$). Phonemic Onset related pictures were also named faster than Unrelated pictures, although this effect reached significance only in the subjects analysis ($t1(19) = 2.31$, $p = .032$; $t2(88) = 0.67$, $p = .505$). In contrast, Semantically related pictures were named significantly slower than Unrelated pictures ($t1(19) = 2.63$, $p = .017$; $t2(88) = 2.74$, $p = .008$).

We also followed up the Relationship Type by Relatedness interaction by examining the effect of Relationship Type at each level of Relatedness. As expected, there was a significant effect of Relationship Type on the related

targets ($F1(2,38) = 41.09$, $p < .001$; $F2(2267) = 20.76$, $p < .001$) because it took participants significantly longer to name the Semantically related targets than the Identity related targets ($t1(19) = 7.10$, $p < .001$, $t2(176) = 6.68$, $p < .001$) or the Phonemic Onset related targets ($t1(19) = 6.81$, $p < .001$, $t2(177) = 3.63$, $p < .001$). Naming times were also significantly longer to the Phonemic Onset related targets than the Identity related targets ($t1(19) = 3.81$, $p < .005$, $t2(177) = 2.64$, $p < .01$). In addition, there was an effect of Relationship Type on the unrelated targets, which reached significance in the subjects analysis ($F1(2,38) = 10.65$, $p < .005$) and approached significance in the items analysis ($F2(2267) = 2.52$, $p = .082$). Again naming times were longer in the Semantic condition than in either the Identity ($t1(19) = 3.51$, $p < .002$, $t2(177) = 1.86$, $p = .065$) or Phonemic Onset ($t1(19) = 5.36$, $p < .001$, $t2(177) = 2.04$, $p < .05$) conditions, although these differences (on average, 64 ms) were much smaller than on the related targets (on average, 165 ms).

The longer times to name the unrelated semantic targets (relative to unrelated targets in the other two conditions) are unlikely to be due to differences in frequency, number of letters, number of phonemes or number of syllables of the names of the targets, or the familiarity of the pictures, which were matched across the three Relationship Types (see Methods). As noted above, there were also more errors in naming the unrelated targets in the Semantic than the Phonemic Onset condition (although not more than in the Identity condition). One possibility therefore is that the picture targets that we used in the Semantic condition were inherently more difficult to name, perhaps because they were more ambiguous than in the other conditions. In order to determine whether any baseline difficulty in naming the target pictures in the semantic condition drove the *interaction* between Relationship Type and Relatedness (e.g. as a result of a psychometric artifact), we carried out two additional analyses. First, for each Relationship Type, we calculated the percentage difference scores (i.e. the difference in naming times between the unrelated and the related conditions divided by the naming times to the unrelated condition) and entered these values into a repeated measures ANOVA. This showed a main effect of Relationship Type, ($F(2,38) = 10.79$, $p = .001$), with follow-up t-tests (examining differences from zero) confirming significant priming effects in the Identity ($t(19) = -3.39$, $p = .003$) and Phonemic Onset ($t(19) = -2.216$, $p = .039$) conditions, but a significant interference effect in the Semantic condition, ($t(19) = 2.487$, $p = .022$). Second, we repeated the subjects analysis on a subset of nine participants who showed no significant difference in naming times to unrelated targets across the three Relationship Types. This also revealed a significant Relationship Type by Relatedness interaction ($F(2,16) = 12.06$, $p = .001$), with follow-ups again showing behavioral Identity priming ($t(8) = -3.746$, $p = .006$), but Semantic interference ($t(8) = 2.600$, $p = .032$); the smaller Phonemic Onset priming effect did not reach significance in this subset ($t(8) = -1.567$, $p = .156$), probably because of a lack of power. We also examined the ERP data in this subset of participants and this showed the same pattern of findings as that reported below.

3.2. ERP results

Voltage maps in the 350–550 ms time window and grand averages of midline ERPs, time-locked to the presentation of target pictures are plotted in Fig. 5. These figures and the

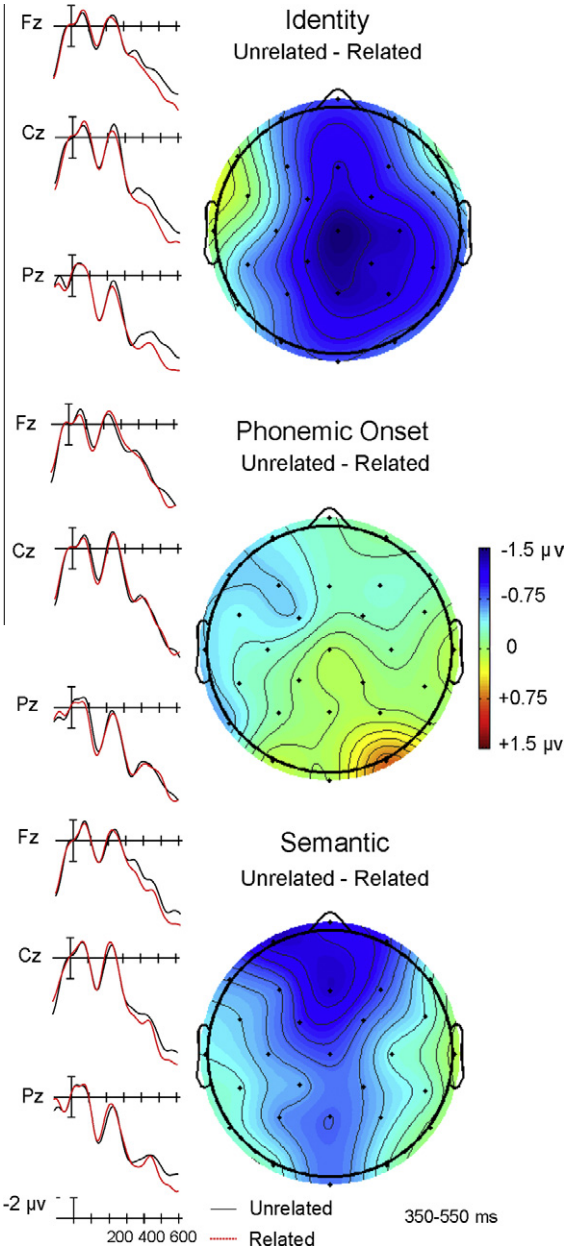

Fig. 5. ERP waveforms and voltage maps. Left: Waveforms shown at frontal, central and parietal sites, time-locked to the presentation of target pictures preceded by Unrelated and Related context words for each of three types of Relationships: Identity related, Semantically related and Phonemic Onset related. Right: Voltage maps of average voltage differences between 350 and 550 ms to target pictures preceded by Unrelated and Related context words for each of the three different types of Relationships. A figure showing these waveforms and voltage maps to only correctly-answered trials can be found at http://www.nmr.mgh.harvard.edu/kuperberglab/materials.htm.

analyses reported below use ERPs averaged across all trials (this had the advantage of maximizing power and maintaining counterbalancing across lists). The ERP results, however, were qualitatively similar when repeated on correctly-answered trials (see supplementary figure at http://www.nmr.mgh.harvard.edu/kuperberglab/materials.htm).

3.2.1. Early effects

Visual inspection of the waveforms indicated no early divergences in the waveforms between 100 and 200 ms or between 200 and 350 ms. This was reflected by the absence of any main effects of Relatedness or interactions between Relationship Type, Relatedness and/or any distributional variables (all $ps > 0.36$, all $Fs < 1.05$).

3.2.2. The N400: 350–550 ms

Analysis of the mean amplitude across the N400 time window through an omnibus ANOVA revealed a main effect of Relatedness ($F(1,19) = 12.29$, $p < 0.005$). There was no two-way interaction between Relatedness and AP Distribution ($F(2,38) = .45$, $p = .552$), or three-way interaction between Relatedness, AP Distribution and Relationship Type ($F(4,76) = .71$, $p = .501$). However, there was a significant interaction between Relationship Type, Relatedness and Laterality ($F(4,76) = 2.59$, $p < 0.05$). This three-way interaction was followed up by examining the effect of Relatedness through 2 (Relatedness) $\times$ 3 (AP Distribution) ANOVAs for each of the three Relationship Types – Identity, Phonemic Onset and Semantic – at each of the three columns (left, midline and right).

Pictures preceded by Identity related words evoked a smaller N400 than pictures preceded by Unrelated words. This effect was quite widespread and significant at all three columns, although the effect was larger in the right column ($F(1,19) = 9.8$, $p < 0.01$) and the midline column ($F(1,19) = 9.07$, $p < 0.01$) than the left column ($F(1,19) = 5.25$, $p < 0.05$). Pictures preceded by Semantically related words also evoked a smaller N400 than those preceded by Unrelated words, but this was primarily centrally distributed; the effect of Relatedness reached significance in the midline column ($F(1,19) = 4.6$, $p < 0.05$), approached significance in the left column ($F(1,19) = 3.35$, $p = 0.08$) but was non-significant in the right column ($F(1,19) = 2.15$, $p = 0.16$). In none of these ANOVAs were there interactions between Relatedness and AP Distribution (all $Fs < 1.57$, all $ps > .225$), indicating that the N400 effects were of equal magnitude across the AP axis of the scalp. In comparing the Phonemic Onset related and Unrelated pairs, there were no main effects of Relatedness or interactions between Relatedness and AP Distribution in any of the three columns (all $Fs < 0.87$, all $ps > 0.37$).

Our finer-grained time-course analysis showed significant differences between the waveforms evoked by the Identity related and Unrelated pictures between 355 and 600 ms, and between the waveforms evoked by Semantically related and Unrelated pictures between 325 and 600 ms. Again, there were no significant differences between waveforms evoked by Phonemic Onset related and Unrelated pictures within the first 600 ms after picture onset.

4. Discussion

The aim of this study was to investigate how manipulations of content at different levels of representation influence speech production by measuring ERPs and naming latencies to pictures preceded by words with different types of relationships to the names of the pictures. Depending on such relationships, ERP and behavioral findings either patterned together or could be dissociated. When pictures were preceded by words that were identical (versus unrelated) to their names, participants showed faster naming times as well as an attenuation of the N400 ERP component, i.e. they showed both behavioral and electrophysiological identity priming. When pictures were preceded by words that had the same phonemic onsets as their names (versus unrelated to their names), participants showed faster naming times (Phonemic Onset behavioral priming), but no differences in the ERP waveform over the 600 ms epoch we analyzed. When pictures were preceded by semantically related (versus unrelated) words, participants showed longer naming times (behavioral semantic interference), but an attenuation of the N400 component (electrophysiological semantic priming). The results from each of these manipulations will be considered in turn.

4.1. Identity relationship

The facilitation of naming times of pictures preceded by an identical context word replicates previous findings of cross-representational identity priming, even when the prime word is presented for very short periods (Glaser & Dungelhoff, 1984; Rosinski et al., 1975). Naming latencies reflect the culmination of multiple processing stages required for production. The attenuation of the N400 to pictures preceded by identity (versus unrelated) words suggests that the priming effect was mediated, in part, by residual activation from the context word at the conceptual and lemma levels of representation, at a stage of word-level semantic processing (Eddy et al., 2006). It is also likely that the observed behavioral facilitation was driven by overlap of phoneme representations at later stages of processing, which were not reflected in the ERP waveform.

4.2. Phonemic Onset relationship

Our finding of Phonemic Onset behavioral facilitation – a Masked Onset Priming Effect (MOPE) – also replicates other studies (Schiller, 2004, 2008). What is interesting is that we saw no differential modulation in the ERP waveform for this contrast within the 600 ms epoch we analyzed (prior to the onset of articulatory artifact). As noted in the Introduction, the precise time-course of access to phonological representations during speech production remains unclear. Indefrey and Levelt (2004) suggested that phonological encoding occurs quite early, between 275 and 400 ms after picture onset, but this conclusion was mainly based on data from early ERP studies using the lateralized readiness potential, which may not generalize to natural word production. Two studies suggest that at least

some phonological information can become available between approximately 300–500 ms after picture onset: first, Vihla et al. (2006) used MEG to show more fronto-temporal activity after 300 ms when participants named or made phonological decisions about pictures, than during a semantic decision task or passive viewing. Second, using the classic picture–word interference task, Dell'Acqua et al. (2010) reported that picture targets with superimposed distractor words, which shared the first two or three phonemes of their names, generated a less negative waveform between 250 and 450 ms than when unrelated distractors were superimposed.

In both of these previous studies, however, effects are likely to have been driven by overlap of phonological word-form representations. In the present study, there was no overlap between the prime and target name past the first phoneme. As discussed in the Introduction, most behavioral studies of the phonemic onset priming effect suggest that it occurs at a later stage, during preparation of the articulatory response (Grainger & Ferrand, 1996; Kinoshita, 2000; Schiller, 2008). Other previous ERP studies support this idea. For example, Schiller (2006) reported an ERP effect with a latency of approximately 500 ms in association with lexical stress encoding (thought to occur in parallel with the retrieval of phoneme representations). Furthermore, Timmer and Schiller (2010), using a word-naming paradigm, demonstrated a behavioral masked onset priming effect but only weak modulation of the ERP waveform in later time windows. Our present findings of a behavioral phonemic onset priming effect, but no electrophysiological phonemic onset priming effect within the epoch we analyzed, adds to this evidence that the retrieval of individual phoneme representations occurs quite late in production. Future studies, analyzing the ERP waveform backwards from the onset of articulation may be able to define the precise timing of access to these representations.

4.3. Semantic relationship

Of most interest was the dissociation we observed between the electrophysiological and behavioral data when the target pictures were preceded by semantically related words. The longer naming times to pictures preceded by semantically related (versus unrelated) context words replicates the semantic interference effect that has been consistently observed in picture naming studies (Bloem et al., 2004; Ehri, 1976; Finkbeiner & Caramazza, 2006; Lupker, 1979; Rosinski, 1977). Strikingly, however, this behavioral interference occurred in the presence of an attenuation of the ERP waveform between 350 and 550 ms, which was smaller (less negative) to related than to unrelated pictures. This ERP modulation – its time-course, scalp distribution and morphology – is similar to that seen in previous studies examining the N400 component to pictures in non-naming tasks (Eddy et al., 2006; McPherson & Holcomb, 1999; Eddy & Holcomb, 2010). It is also similar to two previous ERP studies examining the N400 to pictures in naming tasks (Chauncey et al., 2009; Koester & Schiller, 2008). We therefore take this to be an N400 effect and suggest that its modulation reflected automatic semantic priming.

In theory, there are several possibilities for exactly what representation of the picture was primed by the context word. Our favored interpretation is that priming occurred at the interface between its conceptual and lemma representations, i.e. at a stage of whole-word semantic processing. This is based on a large literature examining the processing of words and pictures that maps modulation within the N400 time window to a mapping between conceptual features and a more abstract, amodal level of semantic representation. This stage of processing is often thought to be shared between comprehension and production (Levelt et al., 1999), and, as discussed in the Introduction, previous production studies have also interpreted modulation within the N400 time window to reflect activity at this level of processing (Chauncey et al., 2009; Koester & Schiller, 2008). According to this interpretation, encountering the context word led to some automatic spread of activation to the conceptual and lemma representations of the target picture (for evidence that N400 modulation may reflect spreading activation under at least partly automatic conditions, see Kiefer, 2002; Kreher, Holcomb, & Kuperberg, 2006), facilitating access to these representations during naming.

It is, however, possible, that rather than reflecting priming at the interface between the conceptual and lemma representations, the N400 attenuation reflected cross-modal priming of the picture's non-verbal conceptual features only. We think that this is unlikely for several reasons. First, even serial models of language production allow for a high degree of interactivity between conceptual and lemma representations (Levelt et al., 1999). Interpreting the N400 as reflecting pure conceptual priming would imply that access to a more abstract semantic representation (the lemma) was delayed past 600 ms. Second, we know that the N400 is not simply sensitive to conceptual features, but also to at least some more abstract lexical information, including lexical frequency (Rugg, 1990; Van Petten & Kutas, 1990), neighborhood size (Holcomb, Grainger, & O'Rourke, 2002) and morphological information (Koester & Schiller, 2008). Third, the waveform that has been most closely associated with the processing of a picture's conceptual features is not the N400, but rather a slightly earlier component which peaks before 400 ms – the N300, which is thought to reflect access to a picture-specific conceptual representation that is invariant to its size, shape or rotation (Barrett & Rugg, 1990; Eddy et al., 2006; McPherson & Holcomb, 1999).[5]

A third possibility is that, rather than reflecting activity at the conceptual/lemma interface, the N400 in this study was influenced by activity at a phonological word-form representation of the picture's name. This type of modality-specific whole-word phonological representation (lexeme) does not appear in Levelt's model, but it is

[5] No N300 attenuation, prior to N400 attenuation, was seen in the present study, although it was seen in the picture naming study by Chauncey et al. (2009). This may be because Chauncey et al. used a longer SOA than in the present study. This may have encouraged some anticipation of conceptual features of the picture stimulus itself, with a spread of activation from the word prime directly to a conceptual/structural level of representation of the picture.

discussed in other models, which place it between conceptual and phonemic representations, instead of (Caramazza, 1997; Starreveld & La Heij, 1996), or in addition to (Cutting & Ferreira, 1999), the lemma. As discussed in the Introduction, there is evidence that the N400 component can be influenced by whole-word phonological information during naming (Jescheniak et al., 2002, 2003). Indeed, there is evidence that some access to a word's phonological information can occur by 200 ms after picture onset (Strijkers et al., 2009, 2011). In the present study, however, naming times were longer than in many of these previous studies, probably because we did not familiarize participants with the pictures ahead of time (see Methods). This is likely to have delayed access to whole-word phonological information. Consistent with this idea, Chauncey et al. (2009), who also did not familiarize participants ahead of time with the names of pictures, reported the same degree of N400 attenuation to target pictures preceded by identity (versus non-identity) primes when bilingual participants named these in their second (versus their first) language. In that case, there was only semantic, but no phonological, overlap between the prime and the name of the target (none were cognates), suggesting that, at least when naming is delayed, the N400 is not necessarily influenced by access to a picture's phonological word-form representation.

Regardless of which of these accounts is correct, the dissociation between electrophysiological semantic priming and behavioral semantic interference sheds light on the debate over the stage of processing in speech production responsible for the behavioral semantic interference effect. If, as we have argued, N400 modulation reflected semantic priming at the interface between conceptual and lemma levels of representation, this places any semantic competition, leading to behavioral semantic interference, past the lemma stage of activation. This argues strongly against an account by which selection occurs by competition at the lemma level, and rather suggests that semantic interference occurs at a later stage of processing. More generally, it provides evidence against Levelt's serial model of production, which assumes that only selected lemmas proceed to phonological encoding (Levelt et al., 1999; Roelofs, 2004). Rather, it suggests a more interactive model with some feedforward influence of competing semantic information at later stages of speech production.

The data presented here cannot pinpoint the precise stage of processing where competition and interference took place. One possibility is that it occurred at the interface between the semantic and phonological word-form representational levels (e.g. Starreveld & La Heij, 1996). This account assumes that access to the phonological word-form representation was delayed and did not influence the N400 component, as discussed above. A second possibility is that, as Caramazza and colleagues have suggested, competition occurred still later during response selection, with the activation of the semantic representation of the context word conflicting with the requirements of the naming task, leading to response interference through a Stroop-like effect (Caramazza & Costa, 2000; Mahon et al., 2007).

We also considered two less likely accounts of the N400 semantic priming effect. First, that it occurred purely through priming of the picture's conceptual features. While this could be reconciled with interference by competition at the lemma level, it would imply that access to the lemma occurred later than 600 ms – much later than Levelt's model assumes (Indefrey & Levelt, 2004). Second, we considered the possibility that the N400 was influenced by activity at the level of phonological word-form representations. This account would place competition and interference at the level of response selection (Caramazza & Costa, 2000; Mahon et al., 2007), once again providing evidence against a serial model of language production.

5. Conclusion

This study shows that combining the temporal acuity of ERPs with overt behavioral picture naming can provide a comprehensive view of the processes involved in speech production. The findings indicate that both Phonemic Onset priming and Semantic interference occur at relatively late stages of speech production. The electrophysiological evidence for semantic priming in the presence of behavioral interference provides evidence against an account of selection by competition at the lemma level, and therefore against purely serial models of speech production. Additional methods of analysis, examining the ERP waveform backwards from naming onset, will be required to determine whether phonemic onset priming and behavioral semantic interference occur at intermediate stages or at very late stages of processing during preparation of the articulatory response.

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Supplementary Material for "A funny thing happened on the way to articulation: N400 attenuation despite behavioral interference in picture naming."

Trevor Blackford, Phillip Holcomb, Jonathan Grainger, and Gina Kuperberg.

The full set of related stimuli for each Relationship Type is shown in alphabetical order. The second item of each pair was presented as a picture. For each Relationship Type, unrelated pairs were constructed by pseudorandomly pairing each target picture and context word.

Identity Relationship

Prime	**<Target>**	**Prime**	**<Target>**	**Prime**	**<Target>**
acorn	<acorn>	hamburger	<hamburger>	shoes	<shoes>
ant	<ant>	hat	<hat>	skate	<skate>
ashtray	<ashtray>	hay	<hay>	skis	<skis>
avocado	<avocado>	horseshoe	<horseshoe>	skull	<skull>
balloon	<balloon>	hose	<hose>	sled	<sled>
baseball	<baseball>	hydrant	<hydrant>	soap	<soap>
basket	<basket>	key	<key>	socks	<socks>
bat	<bat>	kiwi	<kiwi>	spoon	<spoon>
bell	<bell>	ladder	<ladder>	stamp	<stamp>
blender	<blender>	lightbulb	<lightbulb>	stapler	<stapler>
brownie	<brownie>	lighter	<lighter>	strawberry	<strawberry>
cactus	<cactus>	lock	<lock>	sushi	<sushi>
cat	<cat>	matches	<matches>	syringe	<syringe>
clamp	<clamp>	microphone	<microphone>	tank	<tank>
clipboard	<clipboard>	milk	<milk>	teapot	<teapot>
cow	<cow>	olive	<olive>	telescope	<telescope>
desk	<desk>	parrot	<parrot>	thermometer	<thermometer>
dime	<dime>	peanut	<peanut>	tire	<tire>
disk	<disk>	peas	<peas>	toothbrush	<toothbrush>
dog	<dog>	pizza	<pizza>	train	<train>
eggplant	<eggplant>	pretzel	<pretzel>	vase	<vase>
eggs	<eggs>	rabbit	<rabbit>	violin	<violin>
flippers	<flippers>	radiator	<radiator>	waffle	<waffle>
fly	<fly>	raspberry	<raspberry>	wheel	<wheel>
football	<football>	rose	<rose>	wheelchair	<wheelchair>
fork	<fork>	ruler	<ruler>	whistle	<whistle>
giraffe	<giraffe>	sandwich	<sandwich>	wreath	<wreath>
glasses	<glasses>	sausage	<sausage>	yarn	<yarn>
globe	<globe>	saw	<saw>		
goggles	<goggles>	scale	<scale>		
grenade	<grenade>	scissors	<scissors>		

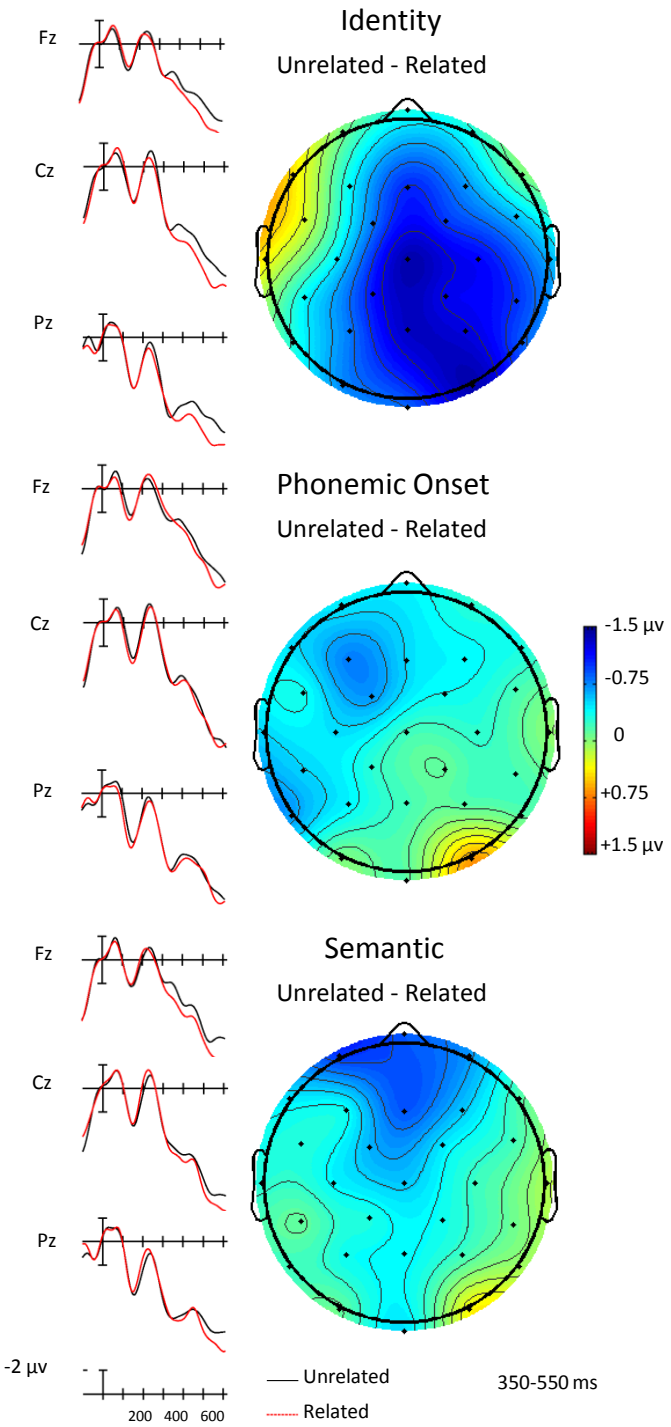
Phonemic Onset Relationship

Prime	<Target>	Prime	<Target>	Prime	<Target>
apricot	<anchor>	hook	<harp>	turnip	<toilet>
bladder	<banana>	headphones	<helicopter>	torpedo	<tomato>
bridge	<bear>	hornet	<helmet>	trolley	<tractor>
brick	<bed>	log	<leaf>	trapeze	<trophy>
bubble	<beetle>	level	<lipstick>	traffic	<trumpet>
bullet	<belt>	melon	<mailbox>	ticket	<turtle>
ball	<bib>	magnet	<mirror>	turntable	<typewriter>
bead	<book>	mushroom	<mousetrap>	unicorn	<umbrella>
blimp	<bowl>	mimosa	<muffin>	vulture	<vacuum>
bench	<bread>	notebook	<necklace>	zeppelin	<zucchini>
bridle	<bucket>	orchid	<orange>		
bone	<bus>	powder	<pacifier>		
barley	<button>	pine	<pen>		
canoe	<camel>	parka	<pencil>		
coyote	<camera>	paddle	<penguin>		
cobweb	<candle>	pedal	<pepper>		
coffin	<cannon>	pawn	<pig>		
coal	<cards>	puzzle	<pillow>		
canal	<carrot>	pier	<pipe>		
chalk	<cheese>	platter	<plunger>		
cheetah	<cherries>	pudding	<potato>		
sedan	<cigar>	prison	<present>		
cloud	<clover>	radio	<racket>		
canary	<coconut>	rifle	<razor>		
castle	<cookie>	rain	<ring>		
card	<corn>	reef	<rock>		
crib	<crow>	skimmer	<scanner>		
dish	<deer>	saddle	<seahorse>		
dice	<doll>	shark	<shell>		
dock	<door>	scarecrow	<skateboard>		
dolphin	<doughnut>	snorkel	<snake>		
drill	<drum>	sparrow	<spider>		
iguana	<eraser>	sperm	<spine>		
fig	<fan>	stomach	<starfish>		
forest	<feather>	stool	<steak>		
flake	<flag>	stretcher	<strainer>		
grinder	<grater>	streamer	<stroller>		
hairbrush	<hammer>	sweetener	<swimsuit>		
hospital	<handcuffs>	tablespoon	<telephone>		
harpoon	<hanger>	typhoon	<toaster>		

Semantic Relationship

Prime	<Target>	Prime	<Target>	Prime	<Target>
pear	<apple>	lemon	<lime>	luggage	<suitcase>
hatchet	<axe>	tiger	<lion>	knife	<sword>
knapsack	<backpack>	reptile	<lizard>	camp	<tent>
sack	<bag>	ape	<monkey>	hurricane	<tornado>
guitar	<banjo>	star	<moon>	car	<truck>
keg	<barrel>	broom	<mop>	suit	<tuxedo>
wasp	<bee>	bike	<motorcycle>	purse	<wallet>
cover	<blanket>	rat	<mouse>	seal	<walrus>
jar	<bottle>	cup	<mug>	clock	<watch>
head	<brain>	pin	<needle>	chain	<whip>
cauliflower	<broccoli>	squid	<octopus>		
moth	<butterfly>	garlic	<onion>		
wagon	<cart>	nightgown	<pajamas>		
turkey	<chicken>	pot	<pan>		
candy	<chocolates>	noodles	<pasta>		
oyster	<clam>	cashew	<peanut>		
flute	<clarinet>	nickel	<penny>		
jacket	<coat>	cologne	<perfume>		
tea	<coffee>	organ	<piano>		
brush	<comb>	cake	<pie>		
protractor	<compass>	dove	<pigeon>		
chair	<couch>	jet	<plane>		
lobster	<crab>	wrench	<pliers>		
cane	<crutch>	squash	<pumpkin>		
pickles	<cucumber>	possum	<raccoon>		
drapes	<curtains>	grape	<raisins>		
horse	<donkey>	hoe	<rake>		
goose	<duck>	hen	<rooster>		
letter	<envelope>	string	<rope>		
tap	<faucet>	carpet	<rug>		
lantern	<flashlight>	trombone	<saxophone>		
wolf	<fox>	necktie	<scarf>		
toad	<frog>	nail	<screw>		
mittens	<gloves>	blouse	<shirt>		
sheep	<goat>	pants	<shorts>		
cricket	<grasshopper>	spade	<shovel>		
pistol	<gun>	fish	<shrimp>		
slacks	<jeans>	cast	<sling>		
light	<lamp>	snail	<slug>		
salad	<lettuce>	chipmunk	<squirrel>		

ERP Waveforms and Voltage Maps to Correctly Named Pictures



Left: Waveforms shown at frontal, central and parietal sites, time-locked to the presentation of correctly-named target pictures preceded by Related and Unrelated context words for each of three types of Relationship: Identity related, Phonemic Onset related and Semantically related.

Right: Voltage maps of average voltage differences between 350-550ms to correctly named target pictures preceded by unrelated and related context words for each of the three types of Relationship.