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## What do we mean by prediction in language comprehension?

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### Abstract

We consider several key aspects of prediction in language comprehension: its computational nature, the representational level(s) at which we predict, whether we use higher level representations to predictively pre-activate lower level representations, and whether we ‘commit’ in any way to our predictions, beyond pre-activation. We argue that the bulk of behavioral and neural evidence suggests that we predict probabilistically and at multiple levels and grains of representation. We also argue that we can, in principle, use higher level inferences to predictively pre-activate information at multiple lower representational levels. We also suggest that the degree and level of predictive pre-activation might be a function of the expected utility of prediction, which, in turn, may depend on comprehenders’ goals and their estimates of the relative reliability of their prior knowledge and the bottom-up input. Finally, we argue that all these properties of language understanding can be naturally explained and productively explored within a multi-representational hierarchical actively generative architecture whose goal is to infer the message intended by the producer, and in which predictions play a crucial role in explaining the bottom-up input.

### Keywords

language comprehension; prediction error; generative model; probabilistic; surprisal

### Introduction

Language processing is predictive. To some, this is a controversial statement. However, under some interpretations, this is something that the field has known for several decades. To consider a well-known and broadly accepted piece of evidence, consider the phenomenon of garden-pathing during sentence comprehension. In sentences like (1a), the comprehender encounters a temporarily ambiguous sequence of words — a context. Upon encountering new bottom-up input (e.g. “conducted”... in (1b)), this ambiguity is resolved to the *a priori* less frequent syntactic interpretation (or parse), leading to processing difficulty. This

increase in processing difficulty is known as the garden path effect, and it manifests both as relatively slower per-word reading times (Ferreira & Clifton, 1986; Garnsey, Pearlmutter, Myers, & Lotocky, 1997; MacDonald, Just, & Carpenter, 1992; Spivey-Knowlton, Trueswell, & Tanenhaus, 1993) and poorer comprehension accuracy (Ferreira, Christianson, & Hollingworth, 2001; Ferreira & Patson, 2007). If, however, the comprehender had encountered another context such as (1c), which avoided the temporary ambiguity, she would not have experienced a garden path effect. Importantly, as we will discuss further in the next section, the magnitude of the garden path effect is graded and highly dependent on the predictability of the intended parse given the preceding context.

(1a) The experienced soldiers warned about the dangers ...

(1b) ... conducted the midnight raid.

(1c) The experienced soldiers who were warned about the dangers ...

Similar effects of contextual predictability are known to influence lexico-semantic processing. Reaction times are faster to predictable versus unpredictable words in a variety of behavioral tasks, ranging from lexical or phrasal decision (Arnon & Snider, 2010; Fischler & Bloom, 1979; Forster, 1981; Schwanenflugel & Lacount, 1988; Schwanenflugel & Shoben, 1985; Stanovich & West, 1983), naming (Forster, 1981; McClelland & O'Regan, 1981; Stanovich & West, 1979, 1981, 1983; Traxler & Foss, 2000), gating (Grosjean, 1980), and speech monitoring (Cole & Perfetti, 1980; Marslen-Wilson, Brown, & Tyler, 1988). Moreover, eye-tracking studies show that readers fixate less on predictable than unpredictable words (Balota, Pollatsek, & Rayner, 1985; Ehrlich & Rayner, 1981; Rayner, Binder, Ashby, & Pollatsek, 2001; Rayner & Well, 1996; see also Boston, Hale, Kliegl, Patil, & Vasishth, 2008; Demberg & Keller, 2008; Demberg, Keller, & Koller, 2013; Frank & Bod, 2011; McDonald & Shillcock, 2003; Smith & Levy, 2013; see Staub, 2015 for a recent review). And, as early as 1980, Kutas and Hillyard reported evidence for a reduced neural signal — the N400 event-related potential (ERP) — to semantically predictable versus unpredictable words in sentence contexts (see also DeLong, Urbach, & Kutas, 2005; Kutas & Federmeier, 2011; Kutas & Hillyard, 1984).

The simple point we wish to make at this stage is that it is logically impossible to explain these effects without assuming that the context influences the *state* of the language processing system *before* the bottom-up input is observed. This is the *minimal* sense in which the language processing system must be predictive. And, indeed, as we will discuss in section 1, almost all models of syntactic parsing and lexico-semantic processing posit that the comprehender has anticipated *some* structure or *some* semantic information prior to encountering new bottom-up information.

Given this logic, the role of prediction in language processing should not be so controversial. Yet, debates about its contributions have been central to psycholinguistic theory for decades, with researchers taking strong positions on both sides. Some, for example, have argued that, given the inherently combinatorial nature of human language, predicting upcoming information ahead of time would be an unnecessary waste of processing resources (see Jackendoff, 2002 and Van Petten & Luka, 2012 for discussion). Others have argued that, given the noisiness, ambiguity and speed of our linguistic input, prediction is the most

efficient solution for fast, efficient and accurate comprehension (e.g. Kleinschmidt & Jaeger, 2015).

These debates can be quite nuanced, with researchers focusing on different aspects of prediction. Some have distinguished *expectation* or *anticipation* from *prediction* (e.g. Van Petten & Luka, 2012); some have distinguished *predictive pre-activation* from *predictive commitment* (e.g. Lau, Holcomb, & Kuperberg, 2013). Finally, within the computational psycholinguistics literature, the term *prediction* has been used in yet other ways, in relation to a growing number of probabilistic models of language processing (e.g., Bejjanki, Clayards, Knill, & Aslin, 2011; Demberg et al., 2013; Feldman, Griffiths, & Morgan, 2009; Hale, 2011; Jurafsky, 1996; Keller, 2003; Kleinschmidt & Jaeger, 2015; Norris & McQueen, 2008; Smith & Levy, 2013).

The end result is that *prediction* has come to mean quite different things to different people. Indeed, our review of the literature led us to the conclusion that different subfields and different researchers have critically different conceptions of what it means to predict during language comprehension. This has led to much confusion with researchers sometimes arguing at cross-purposes. The term *prediction* has become so loaded that some are hesitant to use it at all, while others seem to underestimate (Huettig & Mani, in press) or even reject its role in language processing, despite growing evidence that, in real-world communicative situations, the use of prediction to comprehend language is the norm. It has long been noted that, during natural conversation, we often seem to know when to take our turn, with virtually no gap or overlap between exchanges (Sacks, Schegloff & Jefferson, 1974; Stivers et al., 2009). There is now compelling evidence that these fast exchanges arise because listeners are able to predict when a speaker's conversational turn is about to end, and that such predictions are based on the lexical and syntactic content of what they have just heard (de Ruiter, Mitterer, & Enfield, 2006; Magyari & de Ruiter, 2012, see Garrod & Pickering, 2015 for recent discussion).

This review aims to help clarify some sources of confusion around the role of prediction in language comprehension. Our first goal is to lay out several orthogonal senses in which term *prediction* has been used in the psycholinguistic and cognitive neuroscience literatures, surveying the main debates and pointing to some relevant papers (although, because of space limitations, we do not aim to comprehensively review these literatures). Our second goal is to describe, in qualitative terms, how some of the different psycholinguistic views of prediction can be understood within a probabilistic (Bayesian) *computational* framework. We are not committed to the idea that language processing is strictly Bayesian. Indeed, many of the ideas that we discuss could be instantiated in many different ways at Marr's (1982) algorithmic and implementational levels of analysis. However, we find this framework helpful in articulating, at Marr's computational level, some potential links between psycholinguistic constructs that have been used to understand different aspects of prediction, and this growing computational literature. Our third aim is to summarize some of these insights by sketching out a multi-representational hierarchical actively generative architecture of language comprehension that can potentially explain and link several of the phenomena we discuss.

In section 1, we consider what is meant by *prediction* in the minimal sense of the word, asking whether it is all-or-nothing phenomenon, a graded phenomenon (in which one upcoming possibility is considered at a time) or a parallel graded phenomenon (in which multiple upcoming possibilities are considered in parallel). In section 2, we survey a large body of work suggesting that, at any given time, we can use multiple different types of information in a context to facilitate the processing of new inputs at multiple other levels of representation, ranging from syntactic, semantic, to phonological, orthographic and perceptual. In section 3, we address the debates about whether such facilitation actually reflects the use of higher level information that we have extracted from the context to predictively *pre-activate* information at lower levels of representation, before new bottom-up information becomes available to these lower levels. In section 4, we consider the debates about whether we go beyond pre-activation by pre-updating information at higher levels of representation, incurring additional processing consequences when such commitments are violated by new bottom-up inputs. Finally, in section 5, we summarize the main computational insights gleaned from each section, and we return to the role of prediction in relation to the multi-representational hierarchical actively generative architecture of comprehension that we propose.

## Section 1: The probabilistic nature of contextual prediction

### The data and the debates

As noted above, the minimal sense in which the term *prediction* has been used is to simply imply that context changes the *state* of the language processing system before new input becomes available, thereby facilitating processing of this new input. Throughout this review, we will broadly refer to the internal state that the comprehender has inferred from the context, just ahead of encountering a new bottom-up input as the *internal representation of context*. We postpone the question of whether the comprehender can use high level information within her internal representation of context to predictively pre-activate upcoming information at lower level(s) of representation until section 3. Rather, at this stage, we focus on the nature of prediction itself and discuss the ways in which it has been conceptualized in the literature.

Some older views of prediction conceptualized it as a deterministic, all-or-nothing phenomenon. For example, the original explanations of the garden path phenomenon held that the parser predicted just one possible structure of the sentence — usually the ‘simplest’ structure (which, interestingly, was often the most frequent and therefore the most likely structure, see Ferreira & Clifton, 1986; Frazier, 1978; with aspects of this idea going back to Bever, 1970). If the bottom-up input disconfirmed this predicted structure, the parser needed to back off and fully reanalyze the context in order to come up with the correct interpretation. Similar all-or-nothing assumptions were implicit in early views of lexico-semantic prediction, where prediction also entailed additional assumptions such as necessarily being strategic and attention-demanding (Becker, 1980, 1985; Forster, 1981; Neely, Keefe, & Ross, 1989; Posner & Snyder, 1975; see Kutas, DeLong, & Smith, 2011 for discussion), and they provided plenty of ammunition for arguments against prediction playing any major role in language comprehension: given the huge number of possible

continuations of any given context, it seemed, why bother predicting only to be proved wrong? (see Jackendoff, 2002 and Van Petten & Luka, 2012 for discussion).

More recent accounts view prediction as a graded and probabilistic phenomenon. This view is based on strong evidence of *graded* effects of context on processing. For example, the magnitude of the garden path effect depends on how much a particular verb (Garnsey et al., 1997; Hare, Tanenhaus, & McRae, 2007; Trueswell, Tanenhaus, & Kello, 1993; Wilson & Garnsey, 2009), thematic structure (MacDonald, Pearlmutter, & Seidenberg, 1994; Trueswell, Tanenhaus, & Garnsey, 1994) and/or wider discourse context (Spivey-Knowlton et al., 1993) biases against the intended syntactic parse. Similarly, it is well established that the magnitude of the N400 effect evoked by an incoming word is inversely correlated with that word's probability in relation to its preceding context, as operationalized by its cloze probability<sup>1</sup> (e.g. DeLong et al., 2005; Wlotko & Federmeier, 2012).

Further evidence for probabilistic prediction comes from a series of recent studies reporting a correlation between the surprisal of words and (a) their processing times (Hale, 2001; Levy, 2008) and (b) the neural activity associated with processing them (Frank, Otten, Galli & Vigliococco, 2015). Surprisal is an information theoretic measure that indexes the new Shannon information gained after encountering new input (MacKay, 2003; Shannon, 1948). It is quantified as the logarithm of the inverse of the probability of this input with respect to its context. There is now evidence that processing difficulty, as indexed by reading times, is linearly correlated with surprisal due to more (versus less) predictable parses (Boston et al., 2008; Demberg & Keller, 2008; Frank & Bod, 2011; Hale, 2001; Levy, 2008; Linzen & Jaeger, in press) or words (Boston et al., 2008; Demberg & Keller, 2008; Demberg et al., 2013; Frank & Bod, 2011; McDonald & Shillcock, 2003; Smith & Levy, 2013; see also Arnon & Snider, 2010).<sup>2</sup> There is also recent evidence suggesting that surprisal correlates with the amplitude of the N400 to words within sentences (Frank et al., 2015, see also Rabovsky & McRae, 2014, for discussion of relationships between surprisal and the N400 to words outside sentence contexts).

Based the evidence summarized above, most would agree that prediction is graded in nature. However, there remains some debate about whether it proceeds in a serial or parallel fashion. This debate has been most clearly articulated in the parsing literature. Serial models of parsing hold that just one upcoming structure of a sentence is predicted, with a certain degree of strength, at any particular time. If the bottom-up input mismatches this structure, then the parser reanalyzes and goes on to the next possibility (Traxler, Pickering, & Clifton, 1998; van Gompel, Pickering, Pearson, & Liversedge, 2005; van Gompel, Pickering, & Traxler, 2001). In contrast, parallel models assume that the parser computes multiple syntactic parses in parallel, each with some degree of probabilistic support. This does not

<sup>1</sup>To derive cloze probabilities, a group of participants are presented with a series of sentence contexts and asked to produce the most likely next word for each context. The cloze probability of a given word in a given sentence context is estimated as the proportion of times that particular word is produced over all productions (Taylor, 1953). In addition, the constraint of a context can be calculated by taking the most common completion produced by participants who saw this context, regardless of whether or not this completion matches the word that was actually presented, and tallying the number of participants who provided this completion.

<sup>2</sup>For an alternative conceptualization of the linking function between probabilistic belief updating and reading times, see Hale (2003, 2011). For empirical evaluation and further discussion, see Frank (2013); Linzen and Jaeger (in press); Roark, Bachrach, Cardenas, and Pallier (2009); Wu, Bachrach, Cardenas, and Schuler (2010).

necessarily imply that all possible parses are searched exhaustively, but rather that multiple sufficiently probable parses are considered in parallel (cf. Crocker & Brants, 2000; Jurafsky, 1996; Lewis, 2000; see also Levy, Bicknell, Slattery, & Rayner, 2009, and Traxler, 2014 for discussions of this issue). If the bottom-up input is inconsistent with these predicted parses, they are then shifted or reweighted (Crocker & Brants, 2000; Gorrell, 1987, 1989; Jurafsky, 1996; Levy, 2008; Narayanan & Jurafsky, 2002).

A similar debate has ensued in relation to lexico-semantic prediction. Some have suggested that, because cloze probabilities are derived by averaging across participants and trials (see footnote 1), they are not reflective of what an individual comprehender predicts on any given trial. These researchers assume that the comprehender first predicts the word with the highest cloze probability (the strength of the prediction being related to this probability), and if this is disconfirmed by the bottom-up input, she turns to the word with the next highest cloze probability (Van Petten & Luka, 2012). Others, however, interpret the cloze profile as reflecting the strength/probability of parallel expectations that an individual's brain computes on any given trial. So, for example, if a context has a cloze profile of 55% probability for word X, 25% for word Y and 20% for word Z, then all three possibilities are computed and represented with degrees of belief that correspond to these probabilities; if the bottom-up input turns out to be word Z, then there is a shifting or reweighting of these relative beliefs such that the comprehender now believes continuation Z with nearly 100% probability (DeLong et al., 2005; Wlotko & Federmeier, 2012; see also Staub, Grant, Astheimer, & Cohen, 2015).

In practice, it can often be difficult to experimentally distinguish between serial and parallel probabilistic prediction (for discussion in relation to syntactic prediction, see Gibson & Pearlmutter, 2000; Lewis, 2000; and in relation to lexico-semantic prediction, see Van Petten & Luka, 2012). However, as we discuss below, under certain assumptions, there is a mathematical relationship between surprisal and Bayesian belief updating, which is consistent with the idea that we can predictively compute multiple candidates in parallel, each with different strengths or degrees of belief.

### Computational insights

In his now highly influential work, Anderson (1990) proposed a rational approach to cognition (for discussion, see Simon, 1990). The 'ideal observer' and related models that have grown out of this work have had a tremendous influence on many disciplines in the cognitive sciences (see Chater & Manning, 2006; Clark, 2013; Griffiths, Chater, Kemp, Perfors, & Tenenbaum, 2010; Knill & Pouget, 2004 for reviews, and see Perfors, Tenenbaum, Griffiths, & Xu, 2011, for an excellent introductory overview). This is also true of language processing (e.g., Bejjanki et al., 2011, Chater, Crocker & Pickering, 1998; Clayards, Tanenhaus, Aslin, & Jacobs, 2008; Feldman et al., 2009; Kleinschmidt & Jaeger, 2015; Levy, 2008; Norris, 2006; Norris & McQueen, 2008; see also Crocker & Brants, 2000; Hale, 2001; Jurafsky, 1996; Narayanan & Jurafsky, 2002, for important antecedents of this work in the parsing literature).

Within this framework, the way that a rational comprehender can maximize the probability of accurately recognizing new linguistic input is to use all her stored probabilistic

knowledge, in combination with the preceding context, to process this input. The reason for this is that we communicate in noisy and uncertain environments — there is always uncertainty about the bottom-up input, and neural processing itself is noisy (for reviews and references, see Feldman et al., 2009; Norris, 2006; Shadlen & Newsome, 1994). However, so long as our probabilistic knowledge closely resembles the actual statistics of the linguistic input, then we should be able to use this knowledge to maximize the average probability of correct recognition (see e.g., Bicknell, Tanenhaus, & Jaeger, under review; Kleinschmidt & Jaeger, 2015; Norris & McQueen, 2008, for discussion). Similar arguments hold for the speed of processing new inputs, although here more complex considerations hold (for relevant discussion, see Lewis, Shvartsman, & Singh, 2013; Smith & Levy, 2013), and, indeed, as noted above, there is strong evidence that the speed of processing new input depends on the probability of this input.

To illustrate the principles of how a probabilistic framework can be used to understand the incremental process of sentence comprehension, we describe a model of parsing by Levy (2008; see also Hale, 2003; Jurafsky, 1996; Linzen & Jaeger, in press; Narayanan & Jurafsky, 2002). As in many probabilistic frameworks of cognition, a basic assumption of this model is that, at any given time, the agent's knowledge is encoded by multiple hypotheses. In this case, the parser's probabilistic hypotheses are about the syntactic structure of the sentence. These hypotheses are each held with different strengths or degrees and, in Bayesian terms, are known as beliefs. Together, these beliefs can be described as a probability distribution. The comprehender's goal is to infer the underlying latent or 'hidden' higher level cause of the observed data — the underlying syntactic structure — with as much certainty as possible. To achieve this goal, the parser draws upon a probabilistic grammar (in the broadest sense). Importantly, because the input unfolds linearly, word by word, this goal must be achieved in an incremental fashion — by updating parsing hypotheses after encountering each incoming word. The rational way to update probabilistic beliefs upon receiving new information (new evidence) is by using Bayes' rule, which acts to shift an original prior probability distribution to a new posterior probability distribution. This posterior distribution then becomes the new prior distribution for a new cycle of belief updating when the following word is encountered. In this way, the parser 'homes in on' or discovers the underlying structure of the observed word sequences.

The process of shifting from a prior to a posterior probability distribution on any given cycle is called *belief updating*, and the degree of belief updating as the comprehender shifts from a prior to a posterior distribution is known as Bayesian surprise (Doya, Ishii, Pouget, & Rao, 2007), which is quantified as the Kullback-Leibler divergence between these two probability distributions. Bayesian surprise is therefore one way of computationally formalizing prediction error — the difference between the comprehender's predictions at a given level of representation before and after encountering new input at that level of representation.<sup>3</sup>

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<sup>3</sup>There are, of course, other ways of formalizing prediction error, dating back to Bush & Mosteller (1951) and Rescorla & Wagner (1972). One difference between these formalizations and a Bayesian formalization (Bayesian surprise) is that the former do not take into account uncertainty during inference or prediction (see Kruschke, 2008 for an excellent discussion). Regardless of how it is formalized, however, prediction and prediction error, play a central role in both learning and processing, providing a powerful way of bridging literatures and of potentially linking across computational and algorithmic levels of analysis (see Jaeger & Snider, 2013 and Kuperberg, under review, for discussion).

Unless the parser abandons the process, this cycle of belief updating will continue until it is fairly certain of the structure of the sentence being conveyed. Certainty is represented by the spread or entropy of the probability distribution. Thus, the parser may start out relatively uncertain of the structure of the sentence (described as a relatively flat probability distribution, with small probabilities of belief distributed over multiple possible structures). By the end of the sentence, however, the parser will tend to be more certain of the structure of a sentence (described as a more peaked probability distribution, with high probability beliefs that over this particular structure).

Conceptualizing comprehension as an incremental process of belief updating (and thus probabilistic inference) helps address a potential criticism that is sometimes levied against prediction — even graded forms of prediction: the idea that it might entail costs of suppressing predicted candidates that do not match the bottom-up input. Because all beliefs/hypotheses within a probability distribution must add up to 1, increasing belief about new bottom-up information will necessarily entail decreasing belief over any ‘erroneous’ predictions. While this will entail Bayesian surprise (the shift in belief entailed in transitioning from the prior to the posterior distribution), so will not predicting at all (shifting from a flat high uncertainty prior distribution to a higher certainty posterior distribution).

An important contribution of Levy (2008, see also Levy, 2005) is that he showed that, under certain assumptions, there is a mathematical equivalence between Bayesian surprise and the information theoretic construct of surprisal, which, as noted above is correlated with the processing times and neural activity to words during sentence comprehension. Given that the Bayesian formalization assumes that we hold multiple beliefs in parallel, this equivalence therefore can also be taken to provide indirect support for parallel probabilistic prediction. It also helps explain some phenomena in the ERP literature, for example, why the amplitude of the N400 is large, not only to low probability words that violate highly constraining/predictable sentence contexts, such as “plane” following context (2), but also to low probability words that follow non-constraining contexts, such as “plane” following context (3) (Federmeier, Wlotko, De Ochoa-Dewald, & Kutas, 2007),<sup>4</sup> and indeed to words encountered in isolation of any context (see Kutas & Federmeier, 2011 for a comprehensive review). In all of these cases, the probability of the incoming word is small, and there is a large shift from a prior to a posterior distribution (Bayesian surprise is large; see also Rabovsky & McRae, 2014, for related discussion).

(2) The day was breezy so the boy went outside to fly a...

(3) It was an ordinary day and the boy went outside and saw a...

Levy’s (2008) model, and other probabilistic models of syntactic parsing, are inherently *predictive* because, over each cycle of belief updating, the newly computed posterior probability distribution (the new set of inferred hypotheses) becomes the prior distribution for the next cycle, just before new input is encountered. This new prior probability

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<sup>4</sup>As we will discuss in section 4, however, very low probability incoming words that mismatch the most likely continuation in a highly constraining context can evoke a qualitatively distinct late anterior positivity ERP effect, in addition to the N400 effect.



distribution thus corresponds to *probabilistic predictions* for a new sentence structure at the beginning of the next cycle. These frameworks are also *generative* in nature, in the sense that an underlying syntactic structure can be conceptualized as generating words (Levy, 2008) or word sequences (Bicknell & Levy, 2010; Bicknell, Levy, & Demberg, 2009; Fine, Qian, Jaeger, & Jacobs, 2010; Kleinschmidt, Fine, & Jaeger, 2012), and the comprehender must infer this underlying structure from these observed data.<sup>5</sup> On the other hand, none of these frameworks are *actively* generative: none of them assume that the comprehender's hypotheses about syntactic structure are used to predictively *pre-activate* information at lower levels of representation — that is, change the prior distribution of belief at these lower levels, prior to encountering bottom-up input. We will consider what an actively generative computational framework of language comprehension might look like when we consider predictive pre-activation in section 3.

## Section 2: Using different types of information within a context to facilitate processing of new inputs at multiple levels of representation

### The data and the debates

As noted in section 1, we assume that, just before encountering any new piece of bottom-up information, the comprehender has built an internal representation of context from the linguistic and non-linguistic information in the context that she has encountered thus far. We assume that this internal representation of context includes partial representations inferred from previously processed contextual input, ranging from subphonemic representations (e.g., Bicknell et al., under review; Connine, Blasko, & Hall, 1991; Szostak & Pitt, 2013) all the way up to higher level representations. Such higher level representations may include partial representations of specific events, event structures,<sup>6</sup> event sequences, general schemas (see Altmann & Mirkovic, 2009; Kuperberg, 2013, and McRae & Matsuki, 2009, for reviews and discussion), as well as partial message-level representations (in the sense of Bock & Levelt, 1994, and Dell & Brown, 1991).

In section 1, we discussed the idea that the comprehender can use her representation of context to facilitate syntactic and lexical processing. Syntactic and lexical information, however, are not the only types of information that can be facilitated by context during processing. In this section, we survey the evidence that a comprehender can use information in a context to facilitate the processing of new information at multiple levels of

<sup>5</sup>In this sense, the meaning of the word *generative* has some similarities with Chomsky's original conception of a *generative* syntax, in which a grammar generated multiple possible structures (Chomsky, 1965). There is, however, an important difference: whereas generative grammars in the Chomskyan tradition served to test whether a sentence could be generated from a grammar (in which case it is accepted by that grammar), the generative computational models referred to here represent *distributions* of outputs (e.g., sentences). That is, rather than to stop at the question of whether a sentence can be generated, these models aim to capture how *likely* a sentence is to be generated (although it is worth noting that a generative syntax was formalized in probabilistic terms as early as Booth, 1969, and that probabilistic treatments of grammars have long been acknowledged in the field of sociolinguistics, see Labov, 1969 and Cedergren & Sankoff, 1975 for early discussion).

<sup>6</sup>Here, we refer to knowledge, stored at multiple grains within memory about the conceptual features that are necessary (Chomsky, 1965; Dowty, 1979; Katz & Fodor, 1963), as well as those that are most likely (McRae, Ferretti, & Amyote, 1997) to be associated with a particular semantic-thematic role of an individual event or state. This knowledge might also include the necessary and likely temporal, spatial, and causal relationships that link multiple events and states together to form sequences of events. The latter are sometimes referred to as scripts, frames, or narrative schemas (Fillmore, 2006; Schank & Abelson, 1977; Sitnikova, Holcomb, & Kuperberg, 2008; Wood & Grafman, 2003; Zwaan & Radvansky, 1998).

representation, and that she can draw upon multiple different types of information within her internal representation of context to facilitate such processing. At this point we continue to remain agnostic about whether the comprehender is actually able to use information within her internal representation of context to predictively *pre*-activate upcoming information at lower level(s) of representation prior to bottom-up input reaching these lower levels. We will consider this question in section 3.

There is evidence that a comprehender can use her internal representation of context to facilitate the processing of coarse-grained semantic categories (Altmann & Kamide, 1999; Kamide et al., 2003; Paczynski & Kuperberg, 2011, 2012) as well as finer-grained semantic properties (Altmann & Kamide, 2007; Chambers et al., 2002; Federmeier & Kutas, 1999; Kamide et al., 2003; Kuperberg et al., 2011; Matsuki et al., 2011; Metusalem et al., 2012; Paczynski & Kuperberg, 2012; Xiang & Kuperberg, 2015) of incoming words. This can be taken as evidence that we are able to predict (in the minimal sense, as defined in section 1) the most likely structure of an upcoming event (a representation of ‘who does what to whom’: e.g. Altmann & Kamide, 1999; Garnsey et al., 1997; Hare, McRae, & Elman, 2003; Kamide, Altmann, & Haywood, 2003; Paczynski & Kuperberg, 2011, 2012; Wilson & Garnsey, 2009), quite specific information about an upcoming event (e.g. Chambers, Tanenhaus, Eberhard, Filip, & Carlson, 2002; Kaiser & Trueswell, 2004; Kamide et al., 2003; Matsuki et al., 2011; Metusalem et al., 2012; Paczynski & Kuperberg, 2012), information about future events and states (e.g. Altmann & Kamide, 2007; Hare et al., 2003; Kuperberg, Paczynski, & Ditman, 2011; Pyykkönen & Järvikivi, 2010; Rohde & Horton, 2014; Xiang & Kuperberg, 2015), as well as more general schema information (e.g. Paczynski & Kuperberg, 2012).

In addition, there is a large body of evidence that a comprehender can use her internal representation of context to facilitate the processing of incoming information at multiple other levels of representation. For example, contextual information can lead to facilitated processing of incoming information at the level of syntactic structure (see previous section, and Arai & Keller, 2013; Farmer, Christiansen, & Monaghan, 2006; Garnsey et al., 1997; Gibson & Wu, 2013; Hare et al., 2003; Rohde, Levy, & Kehler, 2011; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995; Wilson & Garnsey, 2009), phonological information (Allopenna, Magnuson, & Tanenhaus, 1998; DeLong et al., 2005) and orthographic information (DeLong et al., 2005; Dikker, Rabagliati, Farmer, & Pykkänen, 2010).

Moreover, this type of facilitation can stem from multiple types of information within a given context. For example, to facilitate semantic processing of new information, comprehenders are able to use information within a verbal context about specific discourse connectives (Rohde & Horton, 2014; Xiang & Kuperberg, 2015), inferential causal relationships (Kuperberg et al., 2011), the selection restrictions of a verb (Altmann & Kamide, 1999; Paczynski & Kuperberg, 2012), the tense of a preceding verb (Altmann & Kamide, 2007), the combination of a specific verb and argument (Kamide et al., 2003; Matsuki et al., 2011; Metusalem et al., 2012; Paczynski & Kuperberg, 2012), pre-verbal arguments (Bornkessel-Schlesewsky & Schlewsky, 2009; Kamide et al., 2003), specific prepositions (Chambers et al., 2002), and prosody (Kurumada, Brown, Bibyk, Pontillo, & Tanenhaus, 2014; Snedeker & Yuan, 2008). Similarly, to facilitate the processing of new

information at the level of syntactic structure, comprehenders can use information within a verbal context about its referential discourse structure (Gibson & Wu, 2013), discourse coherence relationships (Rohde et al., 2011), thematic relationships between verbs and arguments (Garnsey et al., 1997; Wilson & Garnsey, 2009), the specific sense of a verb (Hare et al., 2003), or even their knowledge about a verb's phonological typicality (Farmer et al., 2006). There is also evidence that syntactic information within a context can facilitate the processing of orthographic information (Dikker et al., 2010) or even low level perceptual features (Dikker, Rabagliati, & Pykkänen, 2009). In addition, comprehenders can pick up on *non-verbal* information in the context to influence the processing of a referent (e.g. Knoeferle, Crocker, Scheepers, & Pickering, 2005; Sedivy, Tanenhaus, Chambers, & Carlson, 1999; Tanenhaus et al., 1995).

Taken together, this literature supports the idea that, at any given time, a comprehender's internal representations of context encodes *multiple* different types of information, at different grains of representation (see also Jackendoff, 1987, pages 112-115 for theoretical discussion). How much information is maintained at each of these different levels, and for how long, remains an open question (see, e.g., Bicknell et al., under review; Dahan, 2010), but it seems fair to assume that maintenance of lower level information within the internal representation of context is shorter-lived than higher level information. This literature also highlights the fact that, because language processing is highly interactive, with extensive communication across representational levels during processing (Elman, Hare, & McRae, 2004; McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982), a comprehender can use many of these different types of information, encoded within her internal representation of context, to facilitate the processing of incoming information at almost any other level of representation (see Altmann & Steedman, 1988; Crain & Steedman, 1985; Tanenhaus & Trueswell, 1995, for reviews and discussion). We next consider the computational implications of this type of interactivity for understanding the role of prediction in language comprehension.

### Computational insights

In the probabilistic models of parsing we considered in section 1, the aim of the parser was to infer the structure of the sentence that was being communicated. This structure was conceptualized as generating words or word sequences. Several other generative probabilistic models of language have attempted to model inference at different levels and types of representation. For example, phonetic categories can be understood as generating phonetic cues (Clayards et al., 2008; Feldman et al., 2009; Kleinschmidt & Jaeger, 2015; Sonderegger & Yu, 2010), while semantic categories (Kemp & Tenenbaum, 2008) or topics (Griffiths, Steyvers, & Tenenbaum, 2007; Qian & Jaeger, 2011) can be understood as generating words.

One simplifying feature of all these models is that they each generate just one type of input (although see Brandl, Wrede, Joubin, & Goerick, 2008; Feldman, Griffiths, Goldwater, & Morgan, 2013; Kwiatkowski, Goldwater, Zettlemoyer, & Steedman, 2012, for exceptions in the developmental literature). The ultimate goal of comprehension, however, is not to infer a syntactic structure, a phonemic category, a semantic category or a topic. Rather, it is to infer

its full meaning — the message (Bock, 1987; Bock & Levelt, 1994; Dell & Brown, 1991) or situation model (Johnson-Laird, 1983; Van Dijk & Kintsch, 1983; Zwaan & Radvansky, 1998) that the speaker or writer intends to communicate (Altmann & Mirkovic, 2009; Jaeger & Ferreira, 2013; Kuperberg, 2013; McClelland, St. John, & Taraban, 1989). For a comprehender to infer this message, she must draw upon *multiple* different types of stored information. Given this logic, any complete generative model of language comprehension (the process of language understanding) must consider message-level representations as probabilistically generating information at these multiple types and levels of representation. One way of modeling this type of architecture might be within a multi-representational hierarchical generative framework — the type of framework that been proposed as explaining other aspects of complex cognition (Clark, 2013; Friston, 2005, Hinton 2007; see Farmer, Brown & Tanenhaus, 2013, Pickering & Garrod, 2007, and Brown & Kuperberg, 2015, for perspectives on language processing).

Within such a framework, the comprehender would achieve her goal of inferring the producer's message by incrementally updating her hypotheses about the underlying message being conveyed on the basis of each new piece of information as it becomes available. Such inference and belief updating, which we described for syntactic parsing in section 1, would proceed at *all* levels of the hierarchy of linguistic representation. As discussed in section 1, so long as the comprehender's probabilistic knowledge at these levels of the hierarchy closely resembles the actual statistics of the linguistic input, then she should be able to use it to maximize the average probability of correctly (and perhaps more quickly) recognizing incoming information at these levels of representation. This, in turn, should enable information to pass more efficiently up the hierarchy so that she can update her message-level representation of context (indeed, within some frameworks, such as predictive coding, it is *only* the information that is unpredicted — or 'unexplained' — that is passed up from lower to higher levels of the hierarchy, see Clark, 2013; Friston, 2005). In the next section, we will extend this idea by arguing that, under some circumstances, information does not just flow up the hierarchy, in a bottom-up fashion, but that it can also flow down the hierarchy, with information at higher levels being used, under some circumstances, to *predictively pre-activate* information at lower levels.

### Section 3: Predictive pre-activation

#### The data and the debates

In section 2 we presented further evidence that we can use multiple types of information in the context to *facilitate* processing of new inputs at multiple different representational levels. Facilitation, however, does not necessarily imply predictive pre-activation. To give a concrete example, imagine reading the context in (2) and finding that it can be used to facilitate processing at the phonological level (e.g. the consonant /k<sup>h</sup>/ or the phonemes /k/, /αI/, and /t/). Just before encountering the incoming word “kite”, our internal representation of context is likely to include a hypothesis, held with a high degree of belief, at an event level of representation, that the event being conveyed is <boy flies kite>. In theory, there are two possibilities for how this high level inference/hypothesis might facilitate phonological processing of the incoming word, “kite”. The first is that we wait for the bottom-up input,

“kite”, to activate its phonological representation (and its neighbors), and we *then* use our high level event hypothesis to select the correct phonological representation. The second possibility is that we use our high level event hypothesis to predictively *pre-activate* the phonological representation of “kite” *prior* to the bottom-up input reaching this lower phonological level of representation.

In this section, we discuss this debate about whether or not we can actually predictively pre-activate information at lower representational levels on the basis of information at higher levels within our internal representations of context, ahead of the bottom-up input reaching these lower levels. This debate has a long history in the language processing literature, and has been discussed with respect to the relationships between several different levels and types of representation.

In the speech recognition literature, many researchers would acknowledge that higher level lexical information that has been activated by prior bottom-up phonetic input can be used to predictively pre-activate upcoming potential phonemes, prior to new bottom-up acoustic information arriving at the phonemic level of representation (Dahan & Magnuson, 2006; McClelland & Elman, 1986). In this literature, the main debate has been whether feedback connections from the lexical level to the phonological level can continue to affect the processing of the phonetic/phonological input that is currently being processed, such as lexical activity to *fish* leading to further enhancement of activity to /fl/ (see Norris, 1994; Norris & McQueen, 2008; Norris, McQueen, & Cutler, 2000 for discussion).

In the sentence and discourse processing literatures, there has been more controversy about whether higher level information within our internal representations of context can be used to predictively pre-activate upcoming information at lower levels of representation (see Federmeier, 2007; Kutas et al., 2011 for discussion). Early models argued for lexical predictive pre-activation (Morton, 1969). Later models, however, argued that a message-level representation of context influenced processing of new inputs only *after* lexical (Forster, 1981; Marslen-Wilson, 1987; Swinney, 1979) or more distributed (Gaskell & Marslen-Wilson, 1997; Gaskell & Marslen-Wilson, 1999) representations had been initially activated from the bottom-up input (see Frauenfelder, 1987, for discussion). Only at this stage could this message-level representation exert its effect, acting to select the most appropriate candidates. This slightly later effect of context was said to lead to facilitated *integration* of the incoming word<sup>7</sup>, and it distinguished these frameworks from the more fully interactive activation models from which they were originally inspired (Elman & McClelland, 1984; McClelland & Rumelhart, 1981). While constraint-based models of sentence processing generally remained agnostic as to the role of pre-activation in processing, there was sometimes an implicit assumption that high level contextual influences like plausibility and coherence act primarily to select syntactic frames that had already been activated by the bottom-up lexical input (see Kuperberg, 2007, and Ferreira, 2003, for discussion).

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<sup>7</sup>Note, however, that the term *integration* has been used in different ways in the literature. The usage described here contrasts integration with pre-activation (Federmeier, 2007; see also Van Petten & Luka, 2012, for discussion). Others, however, have used the term *integration* to refer more specifically to the process by which a word is combined or unified with its context to come up with a propositional meaning (e.g. Hagoort, Baggio, & Willems, 2009; Jackendoff, 2002; Lau, Phillips, & Poeppel, 2008).

**Predictive pre-activation versus pre-activation through priming**—One theme that emerged from the lexical, sentence, and discourse processing literatures, was a distinction between pre-activation through top-down prediction, and pre-activation through *priming*.<sup>8</sup> Some researchers distinguished between these processes, allowing pre-activation through priming, but not predictive pre-activation, to influence processing of new bottom-up input. Unlike predictive pre-activation, which entailed the use of high level information within the internal representation of context to pre-activate upcoming information at lower level(s) of representation, priming was assumed to stem from lower level information that was retained with the comprehender's internal representation of context in a relatively raw form. The assumption was that this lingering lower level information might pre-activate upcoming information at this same lower level, through mechanisms such as spreading activation (e.g. Forster, 1981; see also Fodor, 1983).<sup>9</sup> Priming was therefore often viewed as non-targeted (in that activation was taken to spread indiscriminately to related nodes at a single level of representation), and short-term (in that any lingering activation from processing of previous material was assumed to decay rapidly).

Some researchers also assumed other differences between priming and predictive pre-activation. For example, priming was often taken to be non-strategic (in that it serves no purpose), automatic (in that it occurs without conscious control), and sometimes even involuntary (in that it cannot be suppressed). This was again taken to be different from predictive pre-activation, which as noted in section 1, was originally believed to be strategic and sometimes targeted in that only one or a few highly probable candidates were taken to be predicted (Becker, 1980, 1985; Forster, 1981; Neely, Keefe, & Ross, 1989; Posner & Snyder, 1975).

A problem with interpreting this literature, however, is that not every account that appealed to priming subscribed to all of these assumptions, and exactly what distinguished pre-activation through priming from predictive pre-activation was not always made explicit. Moreover, there has sometimes been a tendency to hold on to some older assumptions about both priming and predictive pre-activation. For example, as discussed in section 1, prediction is no longer assumed to be strategic or all-or-nothing, but rather implicit and probabilistic in nature (e.g. DeLong et al., 2005; Federmeier & Kutas, 1999), and there is also evidence that even 'automatic' priming can sometimes be subject to some strategic control (e.g., Hutchison, 2007).

<sup>8</sup>The term, *priming*, is sometimes used simply to describe the phenomenon of facilitated processing of a target that is preceded by a prime, with which it shares one or more representation(s), regardless of mechanism. Pre-activation is just one of these mechanisms. For example, multiple different mechanisms have been proposed to account for the phenomena of both semantic priming (see Neely, 1991 for a review) and syntactic priming (e.g. Chang, Dell, & Bock, 2006; Jaeger & Snider, 2013; Tooley & Traxler, 2010).

<sup>9</sup>For example, memory-based models of text processing assumed that simple lexico-semantic relationships within the internal representation of context, approximating to a 'bag of words' (quantified using measures like Latent Semantic Analysis, Kintsch, 2001; Landauer & Dumais, 1997; Landauer, Foltz, & Laham, 1998), could interact with lexico-semantic relationships stored within long-term memory, and prime upcoming lexico-semantic information through spreading activation (Kintsch, 1988; McKoon & Ratcliff, 1992; Myers & O'Brien, 1998; Sanford, 1990; Sanford & Garrod, 1998). This was known as resonance, and it can be distinguished from the use of high level representations of events or event structures (that include information about 'who does what to whom') to predictively pre-activate upcoming semantic features or categories (see Kuperberg et al., 2011; Lau et al., 2013; Otten & Van Berkum, 2007; Paczynski & Kuperberg, 2012 for discussion).

**Arguments against predictive pre-activation**—By the late 1990s, many psycholinguists were somewhat dubious that predictive pre-activation played much of a role in normal language comprehension (but see Altmann, 1999; Federmeier & Kutas, 1999; Federmeier et al., 2007, and also Tanenhaus et al., 1995, for early discussions of predictive pre-activation in the behavioral and ERP literatures). There was certainly widespread acknowledgment that high level information within the comprehender’s internal representation of context could influence comprehension quickly and incrementally. However, most sentence processing frameworks assumed (either implicitly or explicitly) that such high level information facilitated the processing of new lower level information only *after* this new lower level information had initially been activated by the bottom-up input.

There were several reasons for this skepticism. The first was an intuition that allowing predictive pre-activation to influence processing might afford our prior beliefs too much power, leading to distortions of perceptual or interpretational reality (e.g. Massaro, 1989). These initial concerns, however, may have been overblown. Within the speech recognition literature, there remain some legitimate concerns that *feedback loops* between lexical and phonemic representations might lead to auditory hallucinations (see Norris et al., 2000, p. 302 for discussion). However, under the current proposal, lexical inferences based on *prior* bottom-up input would be used to pre-activate *upcoming* phonemic information. Moreover, we argue that any predictive pre-activation would primarily influence perception in cases when there is relative *uncertainty* about the bottom-up input, as in, for example, the phonemic restoration effect (Warren, 1970), or, more generally, processing in the presence of high degrees of environmental noise (McGowan, 2015; Miller, Heise, & Lichten, 1951; Stilp & Kluender, 2010; Woods, Yund, Herron, & Ua Cruadhlaioich, 2010, reviewed by Davis & Johnsrude, 2007).<sup>10</sup> Similarly, in the sentence processing literature, our prior knowledge, based on real-world knowledge or strongly canonical structures, seems to primarily lead to misinterpretation of the bottom-up input — so-called ‘good enough processing; (Ferreira, 2003) — when there are strong syntactic expectations (for related discussion, see Kuperberg, 2007). The key point is that these phenomena are, in effect, examples of perceptual hallucinations (in the case of speech perception) or ‘cognitive’ hallucinations (in the case of ‘good enough processing’), and the way that they can be explained is precisely through the combination of strong predictive pre-activation and (relative) uncertainty about the bottom-up input.

A second concern that was sometimes raised about predictive pre-activation is similar to that discussed in section 1: that it may entail costs of inhibiting or suppressing predicted candidates that are not supported by the bottom-up input. As we argued in section 1, however, so long as prediction is based on our prior beliefs and the statistics of the input,

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<sup>10</sup>There is, however, also evidence that top-down influences on the perception of lower level information is not the exception, but rather the norm, at least at the lowest levels of speech perception. For example, the internal distributional structure of phonological categories is known to affect the perception of subphonemic acoustic similarity (known as the perceptual magnet effect, Feldman et al., 2009; Kuhl, 1991). This effect has been shown to be a rational consequence of the fact that there is always uncertainty about the perceptual input (due to noise in the neural systems underlying perception). In inferring the percept, comprehenders thus rely on what they know about the statistical structure underlying the speech signal (Feldman et al., 2009; see also Haefner, Berkes, & Fiser, 2014, for a discussion of how sampling-based top-down pre-activation can explain otherwise surprising correlations in firing rates in neural populations).

then, within a purely rational framework of comprehension, the benefits of facilitation should, on average, outweigh the costs.

A third argument against using higher level information in our internal representation of context to predictively pre-activate upcoming information is that doing so might be metabolically costly. Proponents of predictive pre-activation have sometimes ignored this issue, focusing on the idea that, under cost-free assumptions, it is computationally the most efficient way for the comprehender to keep up with the rapidly unfolding bottom-up input. In fact, both sides of the argument are likely to be valid, and when we turn next to computational insights, we will see how it may be possible to formalize the trade off between the costs of predictively pre-activating lower level representation(s), and the benefits of facilitated bottom-up processing at multiple levels of representation.

A final reason why many psycholinguists in the late 1990s were reluctant to endorse predictive pre-activation was that, at the time, there was little direct evidence for it. As discussed in section 2, behavioral and ERP studies provided evidence that higher level information in the internal representation of context could *facilitate* processing of incoming information at multiple lower representational levels. However, as also noted above, it was often possible to argue that such facilitation was not actually due to predictive pre-activation at lower representational levels, but rather due to reduced integration at higher representational levels (see Federmeier, 2007; Kutas et al., 2011). This changed with a series of studies showing that, at least under some circumstances, it was possible to detect behavioral or neural activity to predicted versus unpredicted inputs *before* the onset of these inputs.

First, the visual world paradigm allowed for the measurement of eye movements while participants listened to (and sometimes acted upon) spoken language while viewing an array of images (for an in-depth review of these paradigms and their experimental logic, see Tanenhaus & Trueswell, 2006). If a linguistic context constrains towards the semantic, syntactic or phonological properties of an upcoming word, our eyes tend to move towards images that are related (versus unrelated), along this representational dimension, to the predicted word or referent. Importantly, these eye movements are sometimes anticipatory — detectable before the target word is spoken. There have now been numerous studies using the visual world paradigm, and together they provide strong evidence that, under certain circumstances, we are able to predictively pre-activate upcoming information at multiple representational levels, including syntactic (Arai & Keller, 2013; Kamide, 2012; Tanenhaus et al., 1995), semantic (Altmann & Kamide, 1999; Altmann & Mirkovic, 2009) and phonological (Allopenna et al., 1998) information.

A second line of direct evidence for predictive pre-activation came from a series of ERP studies that reported differential modulation of neural activity prior to the onset of predicted versus unpredicted words. These studies used clever designs in which ERPs were measured to function elements that were dependent on a subsequent predicted content word (DeLong et al., 2005; Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005; Wicha, Moreno, & Kutas, 2004). For example DeLong et al. (2005) showed that, in written contexts like (2), a smaller negativity was evoked by the article “a”, relative to the article “an”. “An”



can only precede words starting with a vowel, and so it is inconsistent with the predicted noun, “kite”. This therefore provides strong evidence for predictive pre-activation — not only for upcoming semantic, but also for upcoming phonological and orthographic information. Other studies using similar types of designs in other languages have shown evidence for predictive pre-activation of syntactic gender (Van Berkum et al., 2005; Wicha et al., 2004), not only during reading but also in spoken language comprehension (Van Berkum et al., 2005). In addition, a recent study using MEG reported increase evoked activity, localizing to the left middle temporal gyrus, in response to the presentation of highly predictive (versus less predictive) adjectives, which was taken to reflect lexical-level pre-activation (Fruchter, Linzen, Westerlund & Marantz, 2015).

Finally, a few MEG studies have reported differential low frequency oscillatory neural activity to contexts that are more versus less predictive for upcoming perceptual features. Unlike evoked ERP or MEG responses, which index phase-locked activity that is time-locked to specific events (Luck, 2014), and which are therefore best suited to detecting facilitation when a new incoming stimulus appears, low frequency oscillatory activity may be better suited for capturing top-down predictive neural activity (for general discussion, see Arnal & Giraud, 2012; Engel & Fries, 2010; Weiss & Mueller, 2012, and for recent discussion in relation to language comprehension, see Lewis & Bastiaansen, 2015). These studies generally used simple contexts that constrained strongly (versus weakly) for the perceptual features of new inputs. They report differential oscillatory activity prior to the appearance of such inputs that localized to early visual (Dikker & Pykkänen, 2013) and auditory (Sohoglu, Peelle, Carlyon, & Davis, 2012) cortices. They therefore provide some suggestive evidence that it is possible to predictively pre-activate upcoming information, even at these low level perceptual representations.

Together, these studies provide strong evidence that, at least under some circumstances, higher level information within our internal representations of context can lead to the pre-activation of incoming information at multiple lower level representations. This is important because it implies that there are no hard architectural or neuroanatomical constraints on the flow of activity activated by our internal representation of context on the processing of new bottom-up inputs. However, it is important to recognize that, just because we *can* use information in a context to pre-activate multiple types of information, this doesn't necessarily mean that we will do so in every situation. Indeed, as we discuss below, several factors have been shown to influence both the degree and the representational level at which upcoming information is predictively pre-activated.

**Factors influencing predictive pre-activation**—The first important factor known to influence predictive pre-activation is the constraint of the context. As discussed above, DeLong et al. (2005) provided evidence that, following highly lexically constraining contexts like (2), predictive pre-activation of the semantic, phonological, and orthographic features of “kite” could modulate the ERP waveform, both before and as the critical word, “kite”, was actually presented. Importantly, these ERP effects were inversely proportional to the lexical constraint of the context, providing strong evidence that lexical constraint of a context can influence the *degree* of pre-activation.

In addition to influencing the degree of pre-activation, there is also evidence that contextual constraint can influence the representational *level* of predictive pre-activation. Highly lexically constraining contexts can influence the very early stages of processing incoming words, suggesting that they can be used to pre-activate information at sublexical levels of representation (see Staub, 2015, for a recent review of the behavioral eye-tracking literature), with evidence from ERP and MEG studies for facilitation on early ERP components (prior to the N400) that reflect phonological (Brothers, Swaab, & Traxler, 2015; Connolly & Phillips, 1994; Groppe et al., 2010), orthographic (Federmeier, Mai, & Kutas, 2005; Kim & Lai, 2012; Lau et al., 2013), or even early perceptual (Dikker & Pykkänen, 2011) processing. Contexts that are less lexically constraining, however, do not appear to modulate these early ERP components, even when they facilitate semantic processing, as reflected by modulation within the N400 time window (e.g. Dikker & Pykkänen, 2011; Paczynski & Kuperberg, 2012, see also Lau et al., 2013).

Most empirical work has focused on the effects of *lexical* constraint, as operationalized using cloze procedures (see footnote 1 in section 1). Contexts that are *lexically* constraining, by definition, constrain strongly for multiple types of representation at the same time (semantic, phonological and syntactic). It is important to recognize however, that a context can constrain strongly for just one type of upcoming representation, leading just to facilitation of incoming information at this representational level, independently of any other. For example, a discourse context can constrain strongly for a general semantic schema (e.g. a restaurant schema), but not for a specific event or specific lexical item, in which case it can lead to facilitated semantic processing of words whose semantic features are related to this schema, as reflected by an attenuation of the N400 ERP component, even when this incoming word is lexically highly unexpected or even anomalous (e.g. Kolk, Chwilla, van Herten, & Oor, 2003; Kuperberg, 2007; Kuperberg, Sitnikova, Caplan, & Holcomb, 2003; Metusalem et al., 2012; Paczynski & Kuperberg, 2012).

A second important factor that can influence predictive pre-activation is the comprehender's current goal. One way of experimentally examining the effect of goal is to manipulate task instructions or demands, and there is indeed evidence that task can influence whether neural (ERP) facilitation is seen to incoming words (for examples, see Chwilla, Brown, & Hagoort, 1995; Kuperberg, 2007; Paczynski & Kuperberg, 2012; Xiang & Kuperberg, 2015; see also McCarthy & Nobre, 1993). For example, in a recent ERP study, Xiang & Kuperberg (2015) showed that, with a requirement to explicitly judge discourse coherence, comprehenders were able to construct a deep situation-level representation of context and use it to access their stored knowledge of real-world event relationships to predict upcoming events, thereby facilitating semantic processing of incoming coherent words. With no such requirement, however, no such semantic facilitation was seen, at least for some types of sentences. There is less work using the visual world paradigm that explicitly contrasts patterns of eye movements with different task instructions. However, there is at least some evidence that task demands can influence the degree to which anticipatory eye movements are seen towards a particular referent (Altmann & Kamide, 1999; Ferreira, Foucart, & Engelhardt, 2013; Sussman, 2006, see Salverda, Brown, & Tanenhaus, 2011 for discussion in relation to the visual world paradigm, and see Hayhoe & Ballard, 2005 for more general discussion).

Goals, of course, are not only influenced by the types of explicit tasks given to participants in psycholinguistic experiments; they play a critical role in everyday language comprehension (see Clark, 1992; Kuperberg, 2007, and Tanenhaus & Brown-Schmidt, 2008, for discussion). As noted above, one can understand the broad goal of comprehension as being to infer the message communicated by the speaker or writer. However, a comprehender's specific goal will depend on the particular situation. During everyday conversation, it will often be to discern the producer's underlying *intention* as conveyed by speech acts (see Brown-Schmidt, Yoon, & Ryskin, 2015; Levinson, 2003; Yoon, Koh, & Brown-Schmidt, 2012 for discussion), and there are now several studies using the visual real-world paradigm showing that the presence or absence of anticipatory eye movements can be influenced by multiple different types of information in both the discourse and non-verbal context, which can cue comprehenders towards carrying out the particular action that the producer intended them to produce (see Salverda et al., 2011; Tanenhaus, Chambers, & Hanna, 2004; Tanenhaus & Trueswell, 2006 for discussion and reviews). For example, Chambers, Tanenhaus, & Magnuson (2004) asked participants to act on spoken instructions like "Pour the egg in the bowl over the flour", and showed that anticipatory eye movements, which reflected participants syntactic parse of the sentence, were influenced by whether or not there were pourable liquid eggs in a bowl (versus solid eggs in a bowl that were not pourable). In addition, when we are listening to a lecture or reading text, our overall goal can also influence mechanism of processing, as well as our future recall of its contents — contrast carefully reading an academic paper with reading a novel for pleasure (see van den Broek, Lorch, Linderholm & Gustafson, 2001 for discussion).

Finally, whether or not we see pre-activation at any particular representational level will likely depend on the speed at which the bottom-up input unfolds: contextual facilitation is greater when linguistic input is presented at slower than faster rates (e.g. Camblin, Ledoux, Boudewyn, Gordon, & Swaab, 2007, Wlotko & Federmeier, 2015). Moreover, the degree to which predictive pre-activation (versus bottom-up input) drives button presses during self-paced reading or eye-movements during reading is known to be sensitive to the relative importance of comprehension speed versus accuracy (see Norris, 2006 for discussion), which can, in turn, be affected by external reward structures (cf. Bicknell, 2011; Bicknell & Levy, 2010; Lewis et al., 2013, see also Lewis, Howes, & Singh, 2014).

Taken together, all these factors suggest that the question we should be asking is not *whether* we can use higher level information in our representation of context to predictively pre-activate upcoming information at lower levels of representation, but rather *when* we do so. We now consider the computational issues that may shed light on the question of when, and to what degree, we use higher level information within our internal representation of context to pre-activate upcoming information at lower representational level(s).

### Computational insights

In computational terms, predictive pre-activation can be understood as the use of beliefs at a higher level of representation (level  $k$ ) to change the *prior* distribution at a lower level of representation ( $k-1$ ), ahead of new bottom-up input reaching this lower level representation. So long as such predictive pre-activation is based on the comprehender's stored probabilistic

knowledge, then, on average, it will serve to reduce the degree of shift that the comprehender *expects* when she encounters new input at this lower level of representation: it will reduce her *expected surprise* at k-1. In other words, by shifting her prior beliefs at k-1 prior to encountering new information at k-1, when such new information does reach k-1, any further shift in belief (Bayesian surprise) will, on average, be less than if she had not pre-activated (shifted the prior at k-1) at all. Information that has been pre-activated at k-1 should therefore, on average, be supported by the new bottom-up input to k-1, and its processing should therefore be relatively facilitated.

Note that an architecture in which inferences at higher levels of representation lead to the generation of predictions at lower level(s) by changing the prior probability belief distributions at these lower levels, is not only generative in the theoretical sense described in sections 1 and 2; it is *actively* generative in the sense that, during real-time processing, information is passed down to lower levels of representation (i.e. higher-level information is used to predictively pre-activate lower level information). This propagation of probabilistic beliefs from higher to lower level representations is said to be subserved by *internal generative models* (Friston, 2005; Hinton, 2007; cf forward models in the motor literature).<sup>11</sup>

Faster recognition at lower levels of representation should enable information to pass more efficiently up the hierarchy to the highest message-level representation. Therefore, if we assume a completely rational framework, predictive pre-activation should, on average, lead to more efficient comprehension. There is, however, an important caveat to this claim: our brains do not have unbounded metabolic resources, and there are likely to be metabolic costs of predictively passing down information from higher to lower level representations (e.g. Attwell & Laughlin, 2001; Laughlin, de Ruyter van Steveninck, & Anderson, 1998). Suppose, for example, a comprehender invested large metabolic costs in passing down information from level k to k-1, then *even if*, on average, Bayesian surprise was less if she had not pre-activated information at k-1, she might still have unnecessarily wasted metabolic resources by pre-activating information at k-1 in the first place (for related discussion, see Norris, 2006, p. 330).

One way of understanding how a comprehender might best trade off the benefits and costs of predictive pre-activation is to assume that she uses the metabolic and cognitive resources she has at her disposal in a rational fashion (e.g., Simon, 1956; Griffiths, Lieder, & Goodman, 2015; Howes, Lewis, & Vera, 2009; for applications and discussion in relation to language processing, see e.g., Bicknell et al. under review; Lewis, Howes, & Singh, 2014; Norris 2006). Within this type of bounded rational framework, both predictive pre-activation, as well as any resulting predictive behavior, can be considered as having a *utility function* that weighs its advantages and disadvantages. The aim of a resource-bound comprehender is to maximize the *utility* of any predictive pre-activation. Below we discuss two mutually compatible ways in which she can do this.

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<sup>11</sup>Actively generative models also provide a link between language comprehension and language production (for discussion, see Jaeger & Ferreira, 2013; Pickering & Garrod, 2007, 2013, and for further discussion of the relationship between prediction in language comprehension and production, see Dell & Chang, 2014; Federmeier, 2007; Garrod & Pickering, 2015; Jaeger & Snider, 2013; Magyari & de Ruiter, 2012).

The first way in which the comprehender can maximize utility is to only predictively pre-activate to the degree and at the level(s) of representation that, on average, serve her ultimate goal. Intuitively, it seems wasteful to predictively pre-activate information when it is not necessary to do so. For example, if our goal is to deeply comprehend a sentence, then we will be likely to use higher level representations (events and event structures) to predictively pre-activate relevant lower levels of representation (including semantic, syntactic, etc.) that will enable us to more efficiently reach our goal. If, however, our goal is to monitor for the word “reviewer”, then we may be more likely to pre-activate the lower levels of representation (e.g. orthographic) that will enable us to most efficiently perform this task.

One way of understanding the role of goal in relation to the type of architecture outlined above, is to conceptualize it as defining the generative model that the agent is employing at any given time, so that the goal is achieved by minimizing Bayesian surprise across the whole model (see Friston et al., 2015, for a more general discussion of the relationships between utility and generative models). Extrapolating to language comprehension, achieving the goal of inferring the producer’s underlying message would entail minimizing Bayesian surprise at the message level representation, as well as the levels of representation below this, to the degree that they allow the comprehender to achieve this goal.

Understanding the role of goal within this type of framework can also help explain how task can influence how much the comprehender values, for instance, speed or accuracy of recognition (for applications of this idea to reading, see Bicknell & Levy, 2012; Lewis et al., 2013; see also Howes et al., 2009). Finally, this framework extends nicely to understanding decisions about behaviors that are predictively triggered as a function their utility. For example, it might potentially explain when anticipatory eye-movements are seen based on the expected gain or utility of such eye-movements (for related discussion, see Hayhoe & Ballard, 2005; for applications to reading, see Bicknell & Levy, 2012; Lewis et al., 2013). More generally, this perspective suggests that a *failure* to observe behavioral evidence of predictive pre-activation at a particular representational level does not necessarily imply that we aren’t *able* to predictively pre-activate information at this level of representation (even when this information is, in principle, available within the preceding context). Since the utility of predictive behaviors depends on task, goal, and stimuli-structure, it is necessary to consider their contributions before concluding that predictive pre-activation at any given representational is not possible. Critically, as noted in the Introduction, there is evidence for predictive behavior during naturalistic language processing tasks (Brown-Schmidt & Tanenhaus, 2008) and in everyday conversation (de Ruiter et al., 2006), suggesting that the utility of predictive pre-activation is relatively high during everyday language processing.

The second (and related) way in which the resource-bound comprehender might be able to maximize the utility of her predictions and rationally allocate resources, is to estimate the *reliability* of both her prior knowledge as well as new input to any given level of representation within her actively generative model, and use these estimates to modulate the *degree* to which she updates her beliefs (for a given prior distribution and likelihood function) at this level of representation (i.e. ‘weight’ prediction error, for related discussion, see Friston, 2010; Feldman & Friston, 2010). Such estimations of reliability may play an important role in allowing us to flexibly adapt comprehension to the demands of a given

situation. For example, during speech perception, it may allow us to quickly recognize familiar individual speakers, generalize our mechanism of processing to similar groups of speakers, accents and dialect, and adapt to novel speakers (see Kleinschmidt & Jaeger, 2015 for discussion), and, as discussed in section 4, it may allow us to comprehend words that violate contexts that are highly lexically constraining.

Finally, this broad utility-based framework could, in theory, accommodate the metabolic costs of predictive pre-activation itself (as well as any metabolic costs of bottom-up message-passing). Such metabolic costs might, for example, be influenced by the speed at which the bottom-up linguistic input unfolds. This is because it presumably takes more energy to pre-activate upcoming information at a given level of representation before this new input arrives at this level of representation, and so we are most likely to predictively pre-activate upcoming lower level information when the input unfolds at a slower rather than a faster rate. The costs of predictive pre-activation are also likely to be influenced by the speed of neural information flow, which is likely to differ between individuals, within individuals across the lifespan (e.g. Federmeier, 2007; Federmeier, Kutas, & Schul, 2010), and which is likely to be affected by different psychopathologies (see Kuperberg, 2007, and Brown & Kuperberg, 2015, for discussion).

In sum, by considering our predictions as having a utility, which is influenced by Bayesian surprise, our goals, as well as the metabolic costs of predictive pre-activation, it may be possible to understand when, to what degree, and at what level(s) of representation we use within our internal representation of context to pre-activate upcoming information at any given time, and to what degree we weight these predictions against new evidence from the bottom-up input.

## Section 4: Predictive pre-updating and the consequences of prediction violation

### The data and the debates

Within the psycholinguistics literature, some have argued that, even if we do use higher level information within our internal representation of context to predictively pre-activate information at lower representational level(s), this still does not constitute true prediction; ‘true’ prediction, these researchers might argue, goes beyond predictive pre-activation by entailing some kind of ‘commitment’ to these pre-activated candidates, ahead of encountering or combining the bottom-up input.

Different researchers have discussed the idea of commitment in different ways. Some have distinguished between a graded pre-activation of multiple candidates, and a predictive commitment to one specific pre-activated candidate such as a single lexical item (Van Petten & Luka, 2012). Others have distinguished between a graded pre-activation of multiple candidates within long-term memory (which we have referred to here as predictive pre-activation), and some kind of commitment to using one (or more) of these candidate(s) to *pre-update* the internal representation of context (e.g. Kamide, 2008; Lau et al., 2013). For example, Lau et al. (2013) suggested that, after reading context (2), just before encountering

the incoming word (“kite”), the comprehender builds a *partial* representation of the event (<boy flies>) within working memory, which she uses to predictively pre-activate lower level representation(s) of <kite> (e.g. its semantic features and its phonological properties) within long-term memory. Pre-updating would refer to the additional step of updating her internal representation of context, within working memory, such that it now contains the pre-activated lower level information in addition to the partial event representation.

One notion that seems to be common to these views is the idea that, if such predictive commitments are *violated* by the bottom-up input (for example, the word “plane” is encountered instead of “kite”), this would lead to a further increase in reaction times or additional neural activity that goes *beyond* what would ensue if the comprehender had not committed in this fashion. These increases in reaction time or prolonged neural activity have sometimes been conceived of as reflecting the costs or consequences of *violating* a strong prediction (see Federmeier, 2007; Kutas et al., 2011, and DeLong et al., 2014 for discussion).

(4a) The day was breezy so the boy went outside to fly a...

(4b) ...kite

(4c) ...plane

(5a) It was an ordinary day and the boy went outside and saw a...

(5b) ...plane

Experimentally, the way researchers have sought evidence for additional neural or behavioral processing associated with violating strong, high certainty predictions is to compare behavioral responses or neural activity to incoming words like “plane” in (4c) that violate contexts like (4a), which constrain very strongly for a different specific lexical item (<kite>), and a different specific event (<boy flies kite>), and incoming words like “plane” (5b) that follow non-constraining (non-predictable) contexts like (5a). Any differences in processing time or neural activity between the critical incoming words in (4c) and (5b) are taken to reflect the additional processing engaged as a result of violating a strong prediction. This difference is compared with another contrast — between (5b) and (4b). In (4b), the critical word is fully supported by the highly constraining context. Any differences in processing time or neural activity between (5b) and (4b) are taken to reflect reduced facilitation (due either to reduced pre-activation at lower level(s) of representation, or reduced integration at the higher event level of representation).

Behavioral studies using this type of logic have found mixed evidence that prediction violations (4c vs. 5b) lead to increased processing, over and above reduced predictive facilitation (5b vs. 4b) (Forster, 1981; Frisson, Rayner & Pickering, 2005; Schwanenflugel & Lacount, 1988; Schwanenflugel & Shoben, 1985; Stanovich & West, 1981, 1983; Traxler & Foss, 2000). One reason for these mixed findings may be that not all of these studies matched the predictability critical words in (4c) and (5b).

Some evidence for additional neural processing that is specifically associated with violating highly constraining contexts as in (4c) has, however, emerged from the ERP literature. While

a full analysis of this literature is outside the scope of this article (see Van Petten & Luka, 2012, and Kuperberg, 2013, for reviews), we note that critical words like (4c) evoke a larger anteriorly distributed late positivity than critical words like (5b). This is the case even when the critical words in these two conditions are matched on their cloze probabilities, and even when they evoke N400s of the same magnitudes (e.g. Federmeier et al., 2007).

There is also evidence for additional prolonged neural processing, beyond that reflected by the N400, in association with words that violate contexts that constrain very strongly for a specific event structure (mappings between semantic and syntactic roles). This additional prolonged processing manifests as another late positivity ERP component with a more posterior scalp distribution, known as the P600 (see Kuperberg, 2007 & 2013 for reviews). Together, these late positivity effects provide some evidence that the brain can incur additional neural consequences when it encounters words that violate highly constraining contexts, over and above those reflected by the N400.

### Computational insights

The psycholinguistic construct of *pre-updating* is compatible with the hierarchical, actively generative architecture discussed in the previous sections. Within this architecture, pre-updating corresponds to the completion of an inference at a particular level of representation, in which the shift from prior to posterior gives rise a very high certainty posterior distribution with belief centered over only very few (and possibly one) high probability hypotheses. This, *in turn*, leads to strong predictive pre-activation at lower levels of representation. Note that this view is somewhat different from the account of predictive pre-updating described above (e.g. Lau et al., 2013), which assumed that predictive pre-activation preceded pre-updating (e.g. after using a partial representation an event, <boy flies>, to predictively pre-activate lower level semantic, syntactic and/or phonological information, only *then* pre-updating the internal representation of context with this pre-activated information). Within a hierarchical actively generative architecture, these stages are reversed: the comprehender is assumed to have *already* pre-updated her belief about the *entire* event that the producer is attempting to convey (<boy flies kite>) – a hypothesis that she holds with a high degree of belief (with a low degree of belief over hypotheses about other possible events, such that her probability distribution over all possible events is high certainty/low entropy). This, in turn, leads her to predictively pre-activate information at lower levels of representation. (Note also that, given that the comprehender's internal representation of context is multi-representational, as discussed in sections 2 and 3, pre-updating is assumed not only to occur at high levels of representation, such as events or event structures, but also at other representational levels. For example, inferring a particular lexical item with a high degree of probability might correspond to pre-updating of beliefs at the lexical level of representation, leading to predictive pre-activation of upcoming phonemes).

One question that remains concerns the neural signatures associated with violations of highly constraining contexts, i.e., the late positivities described above. One possibility is that these late positivities reflect computational mechanisms that go beyond simple belief updating (Bayesian surprise) at any single level of representation. They might, for example,



reflect a process of adaptation (or learning), in which the comprehender updates her entire internal generative model to better reflect the broader statistical structure of the current environment (see Kuperberg, under review, for further discussion; see also Kuperberg, 2013). On this account, after encountering “plane” (instead of “kite”) following context (3a), the comprehender might update her beliefs about the statistical contingencies *between* her semantic, syntactic and phonological knowledge (for computational extensions of this type of generative framework to adaptation during language processing, see Fine et al., 2010; Kleinschmidt et al., 2012; Kleinschmidt & Jaeger, 2015).

A second possibility, which is slightly different although related to the first, is that the late positivities reflect a type of ‘model switching’. For example, the comprehender might have *previously* learned (and stored) different generative models that correspond different statistical environments (Kleinschmidt & Jaeger, 2015, pp180-181; for related models beyond language processing, see also Qian, Jaeger, & Aslin, 2012, and Gershman & Ziv, 2012). For example, comprehenders might have learned generative models for particular genres (Fine, Jaeger, Farmer, & Qian, 2013; Kuperberg, 2013), dialects (Fraundorf & Jaeger, submitted; Niedzielski, 1999), or accents (Hanulíková, van Alphen, van Goch, & Weber, 2012). They might even have learned a generative models for situations in which normal statistics completely break down, e.g., when participating in experiment (cf. Jaeger, 2010, p. 53) or when talking to someone one believes to have a language deficit (Arnold, Kam, & Tanenhaus, 2007). The late positivities might then reflect a re-allocation of resources associated with inferring (or switching to) these new generative models (for further discussion, see Kuperberg, under review). Distinguishing between these possibilities will be an important step in fleshing out the generative architecture described here.

## Section 5: Towards a hierarchical multi-representational generative framework of language comprehension

In this review, we considered several ways in which prediction has been discussed in relation to language comprehension. In section 1, we argued that, in its minimal sense, prediction implies that, at any given time, we use high level information within our representation of context to probabilistically infer (hypothesize) upcoming information at this same higher level representation. In section 2, we surveyed a large body of work suggesting that we can use multiple types of information within our representation of context to facilitate the processing of new bottom-up inputs at multiple other levels of representation, ranging from syntactic, semantic, to phonological, orthographic, and perceptual. In section 3, we discussed evidence that, at least under some circumstances, facilitation at lower level representations results from the use of higher level inferences to *predictively pre-activate* information at these lower level(s), ahead of new bottom-up information reaching these levels. We also discussed several factors known to influence the degree and representational level(s) to which we predictively pre-activate lower level information, suggesting that these factors might act by influencing the *utility* of predictive pre-activation by balancing its benefits and costs. Finally, in section 4, we suggested that, when our high level predictions are particularly certain (corresponding to the psycholinguistic construct of pre-updating),

and the bottom-up turns out to be incompatible with this high-certainty inference, this will lead to additional neural processing, which might reflect adaptation.

In the psycholinguistics literature, the constructs we considered in this review have sometimes been discussed as being qualitatively different to one another. For example, the predictability of information in a context has sometimes been viewed as distinct from pre-activation, and predictive pre-activation has sometimes been viewed as being distinct from pre-updating. Here, however, we have argued that these constructs may be linked by appealing to a hierarchical, dynamic and actively generative framework of language comprehension, in which the comprehender's goal is to infer, with as much certainty as possible, the message-level interpretation or situation model that the producer intends to communicate, at a rate that allows her to keep up with the speed at which the linguistic signal unfolds.

Within this framework, this goal is achieved through incremental cycles of belief updating (Bayesian inference) at multiple levels of representation — the highest message-level representation, as well as at all the levels below that allow the comprehender to achieve her specific goal. We have also suggested that the comprehender actively propagate beliefs/predictions down to successively lower levels of representation (corresponding to predictive pre-activation) in order to minimize expected Bayesian surprise for each new bottom-up input. In this way, when new bottom-up input is encountered, any Bayesian surprise at these lower level representations will be less than if the comprehender had not predictively pre-activated at all. Finally, we have suggested that, by weighting the degree of updating by her estimates of relative reliabilities of her priors and likelihoods at any given level of representation, a comprehender who has bounded resources can achieve this goal more efficiently, quickly and flexibly. Thus, within this type of actively generative framework, prediction is not simply an 'add-on' that aids the recognition of bottom-up input; it plays a pivotal role in driving higher level inference: the goal of comprehension itself.

Of course, there is much work to be done in formalizing and implementing this framework. By adopting a probabilistic framework and discussing the role of prediction in language comprehension at Marr's computational level analysis, we are not claiming that the brain literally computes probabilities, but rather that it may be possible to describe what it is computing in probabilistic terms. In addition, as has sometimes been pointed out, we are consciously aware of only one experience (or, in the case of language, one interpretation) at any one time (see Jackendoff, 1987, pages 115-119, for discussion). It will therefore be important to understand how such probabilistic inference drives our (conscious) comprehension of language (for one theory in the perceptual domain, see Hohwy, Roepstorff & Friston, 2008, and discussion by Clark, 2013, page 184-185). It is also important to note that constructs such as Bayesian surprise can be instantiated in many different ways at the algorithmic and neural levels. For example, key components of incremental belief updating have been implemented within recurrent connectionist networks (e.g. Chang et al., 2006; Dell & Chang, 2014; Elman, 1990; Gaskell, 2003), where there are close links between formalizations of prediction error and Bayesian surprise (see Jaeger & Snider, 2013, McClelland 1998 & 2013 for discussion). Actively generative models have also been instantiated in some neural networks (e.g. Dayan & Hinton, 1996; Dayan, Hinton, Neal, &

Zemel, 1995; Hinton, 2007, see also forward models in the motor literature, e.g. Jordan & Rumelhart, 1992). Finally, it has been proposed that this type of hierarchical actively generative architecture is instantiated at the neural level in the form of predictive coding (Friston, 2005, 2008,<sup>12</sup> see Lewis & Bastiaansen, 2015 and Kuperberg, under review, for discussion in relation to the neural basis of language comprehension), although it is important to recognize that the most direct evidence for predictive coding in the brain comes from Rao and Ballard's (1999) initial descriptions within the visual system. Given these considerations, we believe that this type of multi-representational hierarchical actively generative architecture can potentially provide a powerful bridge across the fields of computational linguistics, psycholinguistics and the neurobiology of language, and we hope that, by sketching out its principles, this will stimulate cross-disciplinary collaboration across these areas.

We conclude by taking up one more important point. In this review, we have mainly focused on the role and value of probabilistic prediction in language comprehension, generally assuming that our probabilistic predictions mirror the statistics of our linguistic and non-linguistic environments. In reality, however, during everyday communication these statistics are constantly changing: every person we converse with will have their own unique style, accent and sets of syntactic and lexical preferences. And every time we read a scientific manuscript, a sci-fi chapter, or a novel by Jane Austen, we will be exposed to quite different statistical structures in our linguistic inputs. As alluded to in sections 3 and 4 (Computational insights), the type of actively generative framework that we have sketched out here is, in fact, well suited for dealing with such variability in our environments. In particular, our ability to weight Bayesian surprise by our estimations of the reliability of the priors and likelihoods may play a more general role in allowing us to rationally allocate resources, allowing us to switch to and/or learn new generative models that are optimally suited to achieving our goals in multiple different communicative environments (for discussion in relation to phonological and speaker-specific adaptation, see Kleinschmidt & Jaeger, 2015, for discussion of other aspects of syntactic, semantic variability and adaptation, see Fine et al., 2013, and for discussion of neural adaptation, in relation to the P600 and other late positivities in language comprehension, see Kuperberg, 2013, and Kuperberg, under review). A key goal for future research will be to understand whether the multi-representational hierarchical actively generative architecture that we have sketched out here can bridge our understanding of the relationships between language processing, adaptation and learning (e.g. Brown-Schmidt et al., 2015; Chang et al., 2006; Dell & Chang, 2014; Jaeger & Snider, 2013).

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<sup>12</sup>Hierarchical predictive coding in the brain takes the principles of the hierarchical generative framework to an extreme by proposing that the flow of bottom-up information from primary sensory cortices to higher level association cortices constitutes *only* the prediction error, i.e. only information that hasn't already been 'explained away' by predictions that have propagated down from higher level cortices (see Clark, 2013; Friston, 2005, 2008; Wacongne et al., 2011 and see Rao & Ballard, 1999 for initial descriptions within the visual system).

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In memory of Bern Milton Jacobson, 1919-2015.

## Bibliography

- Alloppenna PD, Magnuson JS, Tanenhaus MK. Tracking the time course of spoken word recognition using eye movements: Evidence for continuous mapping models. *Journal of Memory and Language*. 1998; 38(4):419–439. doi: 10.1006/jmla.1997.2558.
- Altmann GT. Thematic role assignment in context. *Journal of Memory and Language*. 1999; 41(1): 124–145. doi: 10.1006/jmla.1999.2640.
- Altmann GT, Kamide Y. Incremental interpretation at verbs: restricting the domain of subsequent reference. *Cognition*. 1999; 73(3):247–264. doi: 10.1016/S0010-0277(99)00059-1. [PubMed: 10585516]
- Altmann GT, Kamide Y. The real-time mediation of visual attention by language and world knowledge: Linking anticipatory (and other) eye movements to linguistic processing. *Journal of Memory and Language*. 2007; 57(4):502–518.
- Altmann GT, Mirkovic J. Incrementality and prediction in human sentence processing. *Cognitive Science*. 2009; 33(4):583–609. doi: 10.1111/j.1551-6709.2009.01022.x. [PubMed: 20396405]
- Altmann GT, Steedman M. Interaction with context during human sentence processing. *Cognition*. 1988; 30(3):191–238. doi: 10.1016/0010-0277(88)90020-0. [PubMed: 3215002]
- Anderson, JR. *The Adaptive Character of Thought*. Erlbaum; Hillsdale, NJ: 1990.
- Arai M, Keller F. The use of verb-specific information for prediction in sentence processing. *Language and Cognitive Processes*. 2013; 28(4):525–560. doi: 10.1080/01690965.2012.658072.
- Arnal LH, Giraud AL. Cortical oscillations and sensory predictions. *Trends in Cognitive Sciences*. 2012; 16(7):390–398. doi: 10.1016/j.tics.2012.05.003. [PubMed: 22682813]
- Arnold JE, Kam CL, Tanenhaus MK. If you say thee uh you are describing something hard: the on-line attribution of disfluency during reference comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2007; 33(5):914–930. doi: 10.1037/0278-7393.33.5.914.
- Arnon I, Snider N. More than words: Frequency effects for multi-word phrases. *Journal of Memory and Language*. 2010; 62(1):67–82. doi: 10.1016/j.jml.2009.09.005.
- Attwell D, Laughlin SB. An energy budget for signaling in the grey matter of the brain. *Journal of Cerebral Blood Flow and Metabolism*. 2001; 21(10):1133–1145. doi: 10.1097/00004647-200110000-00001. [PubMed: 11598490]
- Balota DA, Pollatsek A, Rayner K. The interaction of contextual constraints and parafoveal visual information in reading. *Cognitive Psychology*. 1985; 17(3):364–390. doi: 10.1016/0010-0285(85)90013-1. [PubMed: 4053565]
- Becker CA. Semantic context effects in visual word recognition: an analysis of semantic strategies. *Memory and Cognition*. 1980; 8(6):493–512. doi: 10.3758/BF03213769. [PubMed: 7219170]
- Becker, CA. What do we really know about semantic context effects during reading?. In: Besner, D.; Waller, TG.; MacKinnon, EM., editors. *Reading Research: Advances in Theory and Practice*. Vol. 5. Academic Press; Toronto: 1985. p. 125-166.
- Bejjanki VR, Clayards M, Knill DC, Aslin RN. Cue integration in categorical tasks: insights from audio-visual speech perception. *PloS One*. 2011; 6(5):e19812. doi: 10.1371/journal.pone.0019812. [PubMed: 21637344]
- Bever, TG. The cognitive basis for linguistic structures. In: Hayes, JR., editor. *Cognition and the Development of Language*. John Wiley & Sons; New York: 1970. p. 279-362.
- Bicknell, K. Eye movements in reading as rational behavior. University of California; San Diego: 2011. PhD Doctoral dissertation
- Bicknell, K.; Levy, R. A rational model of eye movement control in reading. Paper presented at the Proceedings of the 48th Annual Meeting of the Association for Computational Linguistics (ACL '10); Uppsala, Sweden. 2010.

- Bicknell K, Levy R. The utility of modeling word identification from visual input within models of eye movements in reading. *Visual Cognition*. 2012; 20(4-5):422–456. doi: 10.1080/13506285.2012.668144. [PubMed: 23074362]
- Bicknell, K.; Levy, R.; Demberg, V. Correcting the incorrect: Local coherence effects modeled with prior belief update. Paper presented at the Proceedings of the 35th Annual Meeting of the Berkeley Linguistics Society (BLS); 2009.
- Bicknell, K.; Tanenhaus, MK.; Jaeger, TF. Listeners maintain and rationally update uncertainty about prior words in spoken comprehension. under review
- Bock, JK. Exploring levels of processing in sentence production. In: Kempen, G., editor. *Natural Language Generation*. Martinus Nijhoff; Dordrecht: 1987. p. 351-363.
- Bock, JK.; Levelt, WJM. Language production: Grammatical encoding. In: Gernsbacher, MA., editor. *Handbook of Psycholinguistics*. Academic Press; London: 1994. p. 945-984.
- Booth, TL. Probabilistic representation of formal languages. Paper presented at the IEEE Conference Record of 10th Annual Symposium on Switching and Automata Theory; Waterloo, ON, Canada. 1969.
- Bornkessel-Schlesewsky I, Schlewsky M. The role of prominence information in the real-time comprehension of transitive constructions: a cross-linguistic approach. *Language and Linguistics Compass*. 2009; 3(1):19–58. doi: 10.1111/j.1749-818X.2008.00099.x.
- Boston M, Hale J, Kliegl R, Patil U, Vasishth S. Parsing costs as predictors of reading difficulty: An evaluation using the Potsdam Sentence Corpus. *Journal of Eye Movement Research*. 2008; 2(1):1–12.
- Brandl, H.; Wrede, B.; Joublin, F.; Goerick, C. A self-referential childlike model to acquire phones, syllables and words from acoustic speech. Paper presented at the 7th IEEE International Conference on Development and Learning; Monterey, CA. 2008.
- Brothers T, Swaab TY, Traxler MJ. Effects of prediction and contextual support on lexical processing: prediction takes precedence. *Cognition*. 2015; 136:135–149. doi: 10.1016/j.cognition.2014.10.017. [PubMed: 25497522]
- Brown, M.; Kuperberg, GR. A hierarchical generative framework of language processing: Linking language perception, interpretation, and production abnormalities in schizophrenia. *Frontiers in Human Neuroscience*. 2015.
- Brown-Schmidt S, Tanenhaus MK. Real-time investigation of referential domains in unscripted conversation: a targeted language game approach. *Cognitive Science*. 2008; 32(4):643–684. doi: 10.1080/03640210802066816. [PubMed: 19890480]
- Brown-Schmidt S, Yoon SO, Ryskin RA. People as contexts in conversation. *Psychology of Learning and Motivation*. 2015; 62:59–99. doi: 10.1016/bs.plm.2014.09.003.
- Bush RR, Mosteller F. A mathematical model for simple learning. *Psychological Review*. 1951; 58(5): 313–323. [PubMed: 14883244]
- Camblin CC, Ledoux K, Boudewyn M, Gordon PC, Swaab TY. Processing new and repeated names: Effects of coreference on repetition priming with speech and fast RSVP. *Brain Research*. 2007; 1146:172–184. doi: 10.1016/j.brainres.2006.07.033. [PubMed: 16904078]
- Cedergren HJ, Sankoff D. Variable rules: Performance as a statistical reflection of competence. *Language*. 1974; 50(2):333–355. doi: 10.2307/412441.
- Chambers C, Tanenhaus MK, Eberhard K, Filip H, Carlson GN. Circumscribing referential domains during real-time language comprehension. *Journal of Memory and Language*. 2002; 47(1):30–49. doi: 10.1006/jmla.2001.2832.
- Chambers CG, Tanenhaus MK, Magnuson JS. Actions and affordances in syntactic ambiguity resolution. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2004; 30(3): 687–696. doi: 10.1037/0278-7393.30.3.687.
- Chang F, Dell GS, Bock JK. Becoming syntactic. *Psychological Review*. 2006; 113(2):234–272. doi: 10.1037/0033-295x.113.2.234. [PubMed: 16637761]
- Chater, N.; Crocker, MW.; Pickering, MJ. The rational analysis of inquiry: The case of parsing. In: Oaksford, M.; Chater, N., editors. *Rational Models of Cognition*. Oxford University Press; New York: 1998. p. 441-468.

- Chater N, Manning CD. Probabilistic models of language processing and acquisition. *Trends in Cognitive Sciences*. 2006; 10(7):335–344. doi: 10.1016/j.tics.2006.05.006. [PubMed: 16784883]
- Chomsky, N. *Aspects of the Theory of Syntax*. MIT Press; Cambridge, Mass: 1965.
- Chwilla DJ, Brown CM, Hagoort P. The N400 as a function of the level of processing. *Psychophysiology*. 1995; 32(3):274–285. doi: 10.1111/j.1469-8986.1995.tb02956.x. [PubMed: 7784536]
- Clark A. Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences*. 2013; 36(3):181–204. doi: 10.1017/S0140525X12000477. [PubMed: 23663408]
- Clark, H. *Arenas of language use*. University of Chicago Press; Chicago: 1992.
- Clayards M, Tanenhaus MK, Aslin RN, Jacobs RA. Perception of speech reflects optimal use of probabilistic speech cues. *Cognition*. 2008; 108(3):804–809. doi: 10.1016/j.cognition.2008.04.004. [PubMed: 18582855]
- Cole RA, Perfetti CA. Listening for mispronunciations in a children's story: The use of context by children and adults. *Journal of Verbal Learning and Verbal Behavior*. 1980; 19(3):297–315. doi: 10.1016/s0022-5371(80)90239-x.
- Connine CM, Blasko DG, Hall M. Effects of subsequent sentence context in auditory word recognition: Temporal and linguistic constraint. *Journal of Memory and Language*. 1991; 30(2): 234–250. doi: 10.1016/0749-596x(91)90005-5.
- Connolly JF, Phillips NA. Event-related potential components reflect phonological and semantic processing of the terminal word of spoken sentences. *Journal of Cognitive Neuroscience*. 1994; 6(3):256–266. doi: 10.1162/Jocn.1994.6.3.256. [PubMed: 23964975]
- Crain, S.; Steedman, M. On not being led up the garden path: the use of context by the psychological syntax processor. In: Dowty, DR.; Karttunen, L.; Zwicky, AM., editors. *Natural language parsing: Psychological, computational, and theoretical perspectives*. Cambridge University Press; Cambridge: 1985. p. 320-358.
- Crocker MW, Brants T. Wide-coverage probabilistic sentence processing. *Journal of Psycholinguistic Research*. 2000; 29(6):647–669. doi: 10.1023/A:1026560822390. [PubMed: 11196067]
- Dahan D. The time course of interpretation in speech comprehension. *Current Directions in Psychological Science*. 2010; 19(2):121–126. doi: 10.1177/0963721410364726.
- Dahan, D.; Magnuson, JS. Spoken word recognition. In: Traxler, MJ.; Gernsbacher, MA., editors. *Handbook of Psycholinguistics*. Vol. 2. Academic Press; 2006. p. 249-284.
- Davis MH, Johnsrude IS. Hearing speech sounds: top-down influences on the interface between audition and speech perception. *Hearing Research*. 2007; 229(1-2):132–147. doi: 10.1016/j.heares.2007.01.014. [PubMed: 17317056]
- Dayan P, Hinton GE. Varieties of Helmholtz machine. *Neural Networks*. 1996; 9(8):1385–1403. doi: 10.1016/S0893-6080(96)00009-3. [PubMed: 12662541]
- Dayan P, Hinton GE, Neal RM, Zemel RS. The Helmholtz Machine. *Neural Computation*. 1995; 7(5): 889–904. doi: 10.1162/neco.1995.7.5.889. [PubMed: 7584891]
- de Ruiter JP, Mitterer H, Enfield NJ. Projecting the end of a speaker's turn: A cognitive cornerstone of conversation. *Language*. 2006; 82(3):515–535. doi: 10.1353/lan.2006.0130.
- Dell, GS.; Brown, PM. Mechanisms for listener-adaptation in language production: Limiting the role of the “model of the listener”. In: Napoli, DJ.; Kegl, JA., editors. *Bridges between psychology and linguistics: A Swarthmore Festschrift for Lila Gleitman*. Vol. 105. Psychology Press; 1991. p. 105-129.
- Dell GS, Chang F. The P-chain: relating sentence production and its disorders to comprehension and acquisition. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2014; 369(1634):20120394. doi: 10.1098/rstb.2012.0394.
- DeLong KA, Troyer M, Kutas M. Pre-processing in sentence comprehension: sensitivity to likely upcoming meaning and structure. *Language and Linguistics Compass*. 2014; 8(12):631–645. doi: 10.1111/lnc3.12093.
- DeLong KA, Urbach TP, Kutas M. Probabilistic word pre-activation during language comprehension inferred from electrical brain activity. *Nature Neuroscience*. 2005; 8(8):1117–1121. doi: 10.1038/nn1504. [PubMed: 16007080]

- Demberg V, Keller F. Data from eye-tracking corpora as evidence for theories of syntactic processing complexity. *Cognition*. 2008; 109(2):193–210. doi: 10.1016/j.cognition.2008.07.008. [PubMed: 18930455]
- Demberg V, Keller F, Koller A. Incremental, predictive parsing with psycholinguistically motivated tree-adjoining grammar. *Computational Linguistics*. 2013; 39(4):1025–1066. doi: 10.1162/Coli\_a\_00160.
- Dikker S, Pykkänen L. Before the N400: effects of lexical-semantic violations in visual cortex. *Brain and Language*. 2011; 118(1-2):23–28. doi: 10.1016/j.bandl.2011.02.006. [PubMed: 21458057]
- Dikker S, Pykkänen L. Predicting language: MEG evidence for lexical preactivation. *Brain and Language*. 2013; 127(1):55–64. doi: 10.1016/j.bandl.2012.08.004. [PubMed: 23040469]
- Dikker S, Rabagliati H, Farmer TA, Pykkänen L. Early occipital sensitivity to syntactic category is based on form typicality. *Psychological Science*. 2010; 21(5):629–634. doi: 10.1177/0956797610367751. [PubMed: 20483838]
- Dikker S, Rabagliati H, Pykkänen L. Sensitivity to syntax in visual cortex. *Cognition*. 2009; 110(3): 293–321. doi: 10.1016/j.cognition.2008.09.008. [PubMed: 19121826]
- Dowty, DR. *Word Meaning and Montague Grammar: The Semantics of Verbs and Times in Generative Semantics and in Montague's PTQ*. Reidel, Dordrecht; The Netherlands: 1979.
- Doya, K.; Ishii, S.; Pouget, A.; Rao, RPN., editors. *Bayesian Brain: Probabilistic Approaches to Neural Coding*. MIT Press; Cambridge, MA: 2007.
- Ehrlich SF, Rayner K. Contextual effects on word perception and eye movements during reading. *Journal of Verbal Learning and Verbal Behavior*. 1981; 20(6):641–655. doi: 10.1016/s0022-5371(81)90220-6.
- Elman JL. Finding structure in time. *Cognitive Science*. 1990; 14(2):179–211. doi: 10.1207/s15516709cog1402\_1.
- Elman, JL.; Hare, M.; McRae, K. Cues, constraints, and competition in sentence processing Beyond Nature-Nurture: Essays in Honor of Elizabeth Bates. Lawrence Erlbaum Associates Publishers; Mahwah, NJ: 2004. p. 111-138.
- Elman, JL.; McClelland, JL. Speech perception as a cognitive process: The interactive activation model. In: Lass, N., editor. *Speech and Language*. Vol. 10. Academic Press; New York: 1984.
- Engel AK, Fries P. Beta-band oscillations--signalling the status quo? *Current Opinion in Neurobiology*. 2010; 20(2):156–165. doi: 10.1016/j.conb.2010.02.015. [PubMed: 20359884]
- Farmer TA, Brown M, Tanenhaus MK. Prediction, explanation, and the role of generative models in language processing. *Behavioral and Brain Sciences*. 2013; 36(3):211–212. doi: 10.1017/S0140525X12002312. [PubMed: 23663410]
- Farmer TA, Christiansen MH, Monaghan P. Phonological typicality influences on-line sentence comprehension. *Proceedings of the National Academy of Sciences, USA*. 2006; 103(32):12203–12208. doi: 10.1073/pnas.0602173103.
- Federmeier KD. Thinking ahead: the role and roots of prediction in language comprehension. *Psychophysiology*. 2007; 44(4):491–505. doi: 10.1111/j.1469-8986.2007.00531.x. [PubMed: 17521377]
- Federmeier KD, Kutas M. A rose by any other name: Long-term memory structure and sentence processing. *Journal of Memory and Language*. 1999; 41(4):469–495. doi: 10.1006/Jmla.1999.2660.
- Federmeier KD, Kutas M, Schul R. Age-related and individual differences in the use of prediction during language comprehension. *Brain and Language*. 2010; 115(3):149–161. doi: 10.1016/j.bandl.2010.07.006. [PubMed: 20728207]
- Federmeier KD, Mai H, Kutas M. Both sides get the point: hemispheric sensitivities to sentential constraint. *Memory and Cognition*. 2005; 33(5):871–886. doi: 10.3758/BF03193082. [PubMed: 16383175]
- Federmeier KD, Wlotko EW, De Ochoa-Dewald E, Kutas M. Multiple effects of sentential constraint on word processing. *Brain Research*. 2007; 1146:75–84. doi: 10.1016/j.brainres.2006.06.101. [PubMed: 16901469]
- Feldman H, Friston KJ. Attention, uncertainty, and free-energy. *Frontiers in Human Neuroscience*. 2010; 4:215. doi: 10.3389/fnhum.2010.00215. [PubMed: 21160551]

- Feldman NH, Griffiths TL, Goldwater S, Morgan JL. A role for the developing lexicon in phonetic category acquisition. *Psychological Review*. 2013; 120(4):751–778. doi: 10.1037/a0034245. [PubMed: 24219848]
- Feldman NH, Griffiths TL, Morgan JL. The influence of categories on perception: explaining the perceptual magnet effect as optimal statistical inference. *Psychological Review*. 2009; 116(4):752–782. doi: 10.1037/a0017196. [PubMed: 19839683]
- Ferreira F. The misinterpretation of noncanonical sentences. *Cognitive Psychology*. 2003; 47:164–203. doi: 10.1016/S0010-0285(03)00005-7. [PubMed: 12948517]
- Ferreira F, Christianson K, Hollingworth A. Misinterpretations of garden-path sentences: Implications for models of sentence processing and reanalysis. *Journal of Psycholinguistic Research*. 2001; 30(1):3–20. doi: 10.1023/a:1005290706460. [PubMed: 11291182]
- Ferreira F, Clifton C Jr. The independence of syntactic processing. *Journal of Memory and Language*. 1986; 25:348–368. doi: 10.1016/0749-596X(86)90006-9.
- Ferreira F, Foucart A, Engelhardt PE. Language processing in the visual world: Effects of preview, visual complexity, and prediction. *Journal of Memory and Language*. 2013; 69(3):165–182. doi: 10.1016/j.jml.2013.06.001.
- Ferreira F, Patson ND. The 'good enough' approach to language comprehension. *Language and Linguistics Compass*. 2007; 1(1-2):71–83. doi: 10.1111/j.1749-818X.2007.00007.x.
- Fillmore CJ. Frame semantics. *Cognitive Linguistics: Basic Readings*. 2006; 34:373–400. doi: 10.1515/9783110199901.373.
- Fine AB, Jaeger TF, Farmer TA, Qian T. Rapid expectation adaptation during syntactic comprehension. *PLoS One*. 2013; 8(10):e77661. doi: 10.1371/journal.pone.0077661. [PubMed: 24204909]
- Fine, AB.; Qian, T.; Jaeger, TF.; Jacobs, RA. Is there syntactic adaptation in language comprehension?. Paper presented at the Proceedings of the 2010 Workshop on Cognitive Modeling and Computational Linguistics (CMCL '10); Uppsala, Sweden. 2010.
- Fischler IS, Bloom PA. Automatic and attentional processes in the effects of sentence contexts on word recognition. *Journal of Verbal Learning and Verbal Behavior*. 1979; 5:1–20. doi: 10.1016/S0022-5371(79)90534-6.
- Fodor, JA. *The modularity of mind: an essay on faculty psychology*. MIT Press; Cambridge, M.A.: 1983.
- Forster KI. Priming and the effects of sentence and lexical contexts on naming time: Evidence for autonomous lexical processing. *Quarterly Journal of Experimental Psychology. A: Human Experimental Psychology*. 1981; 33(4):465–495. doi: 10.1080/14640748108400804.
- Frank SL. Uncertainty reduction as a measure of cognitive load in sentence comprehension. *Topics in Cognitive Science*. 2013; 5(3):475–494. doi: 10.1111/tops.12025. [PubMed: 23681508]
- Frank SL, Bod R. Insensitivity of the human sentence-processing system to hierarchical structure. *Psychological Science*. 2011; 22(6):829–834. doi: 10.1177/0956797611409589. [PubMed: 21586764]
- Frank SL, Otten LJ, Galli G, Vigliocco G. The ERP response to the amount of information conveyed by words in sentences. *Brain and Language*. 2015; 140:1–11. doi: 10.1016/j.bandl.2014.10.006. [PubMed: 25461915]
- Frauenfelder UH, Tyler LK. The process of spoken word recognition: An introduction. *Cognition*. 1987; 25:1–20. doi: 10.1016/0010-0277(87)90002-3. [PubMed: 3581722]
- Fraudorf, S.; Jaeger, TF. Readers generalize priming of newly-encountered dialectal structures to other unfamiliar structures. submitted
- Frazier, L. *On comprehending sentences: Syntactic parsing strategies*. University of Connecticut; Storrs, CT: 1978. Doctoral dissertation
- Frisson S, Rayner K, Pickering MJ. Effects of contextual predictability and transitional probability on eye movements during reading. *Journal of Experimental Psychology. Learning, memory, and cognition*. 2005; 31(5):862–877. doi: 10.1037/0278-7393.31.5.862.
- Friston KJ. A theory of cortical responses. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2005; 360(1456):815–836. doi: 10.1098/Rstb.2005.1622.
- Friston KJ. Hierarchical models in the brain. *PLoS Computational Biology*. 2008; 4(11):e1000211. doi: 10.1371/journal.pcbi.1000211. [PubMed: 18989391]



- Friston KJ. The free-energy principle: a unified brain theory? *Nature Reviews Neuroscience*. 2010; 11(2):127–138. doi: 10.1038/nrn2787. [PubMed: 20068583]
- Friston KJ, Rigoli F, Ognibene D, Mathys C, Fitzgerald T, Pezzulo G. Active inference and epistemic value. *Cognitive Neuroscience*. 2015:1–28. doi: 10.1080/17588928.2015.1020053.
- Fruchter J, Linzen T, Westerlund M, Marantz A. Lexical preactivation in basic linguistic phrases. *Journal of Cognitive Neuroscience*. 2015; 27(10):1912–1935. doi: 10.1162/jocn\_a\_00822. [PubMed: 25961637]
- Garnsey SM, Pearlmutter NJ, Myers E, Lotocky MA. The contributions of verb bias and plausibility to the comprehension of temporarily ambiguous sentences. *Journal of Memory and Language*. 1997; 37(1):58–93. doi: 10.1006/Jmla.1997.2512.
- Garrod S, Pickering MJ. The use of content and timing to predict turn transitions. *Frontiers in Psychology*. 2015; 6:751. doi: 10.3389/fpsyg.2015.00751. [PubMed: 26124728]
- Gaskell MG. Modelling regressive and progressive effects of assimilation in speech perception. *Journal of Phonetics*. 2003; 31(3-4):447–463. doi: 10.1016/S0095-4470(03)00012-3.
- Gaskell MG, Marslen-Wilson WD. Integrating form and meaning: A distributed model of speech perception. *Language and Cognitive Processes*. 1997; 12(5-6):613–656. doi: 10.1080/016909697386646.
- Gaskell MG, Marslen-Wilson WD. Ambiguity, competition, and blending in spoken word recognition. *Cognitive Science*. 1999; 23(4):439–462. doi: 10.1207/s15516709cog2304\_3.
- Gershman SJ, Niv Y. Exploring a latent cause theory of classical conditioning. *Learning and Behavior*. 2012; 40(3):255–268. doi: 10.3758/s13420-012-0080-8. [PubMed: 22927000]
- Gibson E, Pearlmutter NJ. Distinguishing serial and parallel parsing. *Journal of Psycholinguistic Research*. 2000; 29(2):231–240. doi: 10.1023/a:1005153330168. [PubMed: 10709187]
- Gibson E, Wu HHI. Processing Chinese relative clauses in context. *Language and Cognitive Processes*. 2013; 28(1-2):125–155. doi: 10.1080/01690965.2010.536656.
- Correll, PG. Studies of human syntactic processing: Ranked-parallel versus serial models. University of Connecticut; Storrs, CT: 1987. Doctoral dissertation
- Correll PG. Establishing the loci of serial and parallel effects in syntactic processing. *Journal of Psycholinguistic Research*. 1989; 18(1):61–73. doi: 10.1007/bf01069047.
- Griffiths TL, Chater N, Kemp C, Perfors A, Tenenbaum JB. Probabilistic models of cognition: exploring representations and inductive biases. *Trends in Cognitive Sciences*. 2010; 14(8):357–364. doi: 10.1016/j.tics.2010.05.004. [PubMed: 20576465]
- Griffiths TL, Lieder F, Goodman ND. Rational use of cognitive resources: levels of analysis between the computational and the algorithmic. *Topics in Cognitive Science*. 2015; 7(2):217–229. doi: 10.1111/tops.12142. [PubMed: 25898807]
- Griffiths TL, Steyvers M, Tenenbaum JB. Topics in semantic representation. *Psychological Review*. 2007; 114(2):211–244. doi: 10.1037/0033-295X.114.2.211. [PubMed: 17500626]
- Grope DM, Choi M, Huang T, Schilz J, Topkins B, Urbach TP, Kutas M. The phonemic restoration effect reveals pre-N400 effect of supportive sentence context in speech perception. *Brain Research*. 2010; 1361:54–66. doi: 10.1016/J.Brainres.2010.09.003. [PubMed: 20831863]
- Grosjean F. Spoken word recognition processes and the gating paradigm. *Perception and Psychophysics*. 1980; 28(4):267–283. doi: 10.3758/bf03204386. [PubMed: 7465310]
- Haefner, RM.; Berkes, P.; Fiser, J. Perceptual decision-making as probabilistic inference by neural sampling. 2014. arXiv preprint arXiv:1409.0257
- Hagoort, P.; Baggio, G.; Willems, RM. Semantic unification. In: Gazzaniga, MS., editor. *The Cognitive Neurosciences*. 4th. MIT Press; Cambridge, MA: 2009. p. 819-836.
- Hale, J. A probabilistic Earley parser as a psycholinguistic model. Paper presented at the Proceedings of the North American Chapter of the Association for Computational Linguistics on Language technologies (NAACL '01); 2001.
- Hale J. The information conveyed by words in sentences. *Journal of Psycholinguistic Research*. 2003; 32(2):101–123. doi: 10.1023/A:1022492123056. [PubMed: 12690827]
- Hale J. What a rational parser would do. *Cognitive Science*. 2011; 35(3):399–443. doi: Doi 10.1111/J.1551-6709.2010.01145.X.

- Hanulikova A, van Alphen PM, van Goch MM, Weber A. When one person's mistake is another's standard usage: The effect of foreign accent on syntactic processing. *Journal of Cognitive Neuroscience*. 2012; 24(4):878–887. doi: 10.1162/jocn\_a\_00103. [PubMed: 21812565]
- Hare M, McRae K, Elman JL. Sense and structure: Meaning as a determinant of verb subcategorization preferences. *Journal of Memory and Language*. 2003; 48(2):281–303. doi: 10.1016/s0749-596x(02)00516-8.
- Hare M, Tanenhaus MK, McRae K. Understanding and producing the reduced relative construction: Evidence from ratings, editing and corpora. *Journal of Memory and Language*. 2007; 56(3):410–435. doi: 10.1016/j.jml.2006.08.007. [PubMed: 22162904]
- Hayhoe M, Ballard D. Eye movements in natural behavior. *Trends in Cognitive Sciences*. 2005; 9(4): 188–194. doi: 10.1016/j.tics.2005.02.009. [PubMed: 15808501]
- Hinton GE. Learning multiple layers of representation. *Trends in Cognitive Sciences*. 2007; 11(10): 428–434. doi: 10.1016/j.tics.2007.09.004. [PubMed: 17921042]
- Hohwy J, Roepstorff A, Friston K. Predictive coding explains binocular rivalry: an epistemological review. *Cognition*. 2008; 108(3):687–701. doi: 10.1016/j.cognition.2008.05.010. [PubMed: 18649876]
- Howes A, Lewis RL, Vera A. Rational adaptation under task and processing constraints: implications for testing theories of cognition and action. *Psychological Review*. 2009; 116(4):717–751. doi: 10.1037/a0017187. [PubMed: 19839682]
- Huetting F, Mani N. Is prediction necessary to understand language? Probably not. *Language, Cognition and Neuroscience*. in press.
- Hutchison KA. Attentional control and the relatedness proportion effect in semantic priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2007; 33(4):645–662. doi: 10.1037/0278-7393.33.4.645.
- Jackendoff, R. *Language processing Consciousness and the Computational Mind*. MIT Press; Cambridge, MA: 1987. p. 91-120.
- Jackendoff, R. *Foundations of Language: Brain, Meaning, Grammar, Evolution*. Oxford University Press; New York: 2002.
- Jaeger TF. Redundancy and reduction: speakers manage syntactic information density. *Cognitive Psychology*. 2010; 61(1):23–62. doi: 10.1016/j.cogpsych.2010.02.002. [PubMed: 20434141]
- Jaeger TF, Ferreira V. Seeking predictions from a predictive framework. *Behavioral and Brain Sciences*. 2013; 36(4):359–360. doi: 10.1017/S0140525X12002762. [PubMed: 23789872]
- Jaeger TF, Snider NE. Alignment as a consequence of expectation adaptation: syntactic priming is affected by the prime's prediction error given both prior and recent experience. *Cognition*. 2013; 127(1):57–83. doi: 10.1016/j.cognition.2012.10.013. [PubMed: 23354056]
- Johnson-Laird, PN. *Mental Models*. Harvard University Press; Cambridge: 1983.
- Jordan MI, Rumelhart DE. Forward models: Supervised learning with a distal teacher. *Cognitive Science*. 1992; 16(3):307–354. doi: 10.1207/s15516709cog1603\_1.
- Jurafsky D. A probabilistic model of lexical and syntactic access and disambiguation. *Cognitive Science*. 1996; 20(2):137–194. doi: 10.1016/s0364-0213(99)80005-6.
- Kaiser E, Trueswell JC. The role of discourse context in the processing of a flexible word-order language. *Cognition*. 2004; 94(2):113–147. doi: 10.1016/j.cognition.2004.01.002. [PubMed: 15582623]
- Kamide Y. Anticipatory processes in sentence processing. *Language and Linguistics Compass*. 2008; 2(4):647–670. doi: 10.1111/j.1749-818X.2008.00072.x.
- Kamide Y. Learning individual talkers' structural preferences. *Cognition*. 2012; 124(1):66–71. doi: 10.1016/j.cognition.2012.03.001. [PubMed: 22498776]
- Kamide Y, Altmann GT, Haywood SL. The time-course of prediction in incremental sentence processing: Evidence from anticipatory eye movements. *Journal of Memory and Language*. 2003; 49:133–156.
- Katz JJ, Fodor JA. The structure of a semantic theory. *Language*. 1963; 39:170–210.
- Keller, F. A probabilistic parser as a model of global processing difficulty. Paper presented at the Proceedings of the 25th Annual Conference of the Cognitive Science Society; Boston. 2003.

- Kemp C, Tenenbaum JB. The discovery of structural form. *Proceedings of the National Academy of Sciences, USA*. 2008; 105(31):10687–10692. doi: 10.1073/pnas.0802631105.
- Kim A, Lai V. Rapid interactions between lexical semantic and word form analysis during word recognition in context: evidence from ERPs. *Journal of Cognitive Neuroscience*. 2012; 24(5): 1104–1112. doi: 10.1162/jocn\_a\_00148. [PubMed: 21981670]
- Kintsch W. The role of knowledge in discourse comprehension: A construction-integration model. *Psychological Review*. 1988; 95:163–182. doi: 10.1037/0033-295X.95.2.163. [PubMed: 3375398]
- Kintsch W. Predication. *Cognitive Science*. 2001; 25(173-202) doi: 10.1207/s15516709cog2502\_1.
- Kleinschmidt, DF.; Fine, AB.; Jaeger, TF. A belief-updating model of adaptation and cue combination in syntactic comprehension. In: Miyake, N.; Peebles, D.; Cooper, RP., editors. *Proceedings of the 34th Annual Conference of the Cognitive Science Society*; Sapporo, Japan: Cognitive Science Society; 2012. p. 605-610.
- Kleinschmidt DF, Jaeger FT. Robust speech perception: Recognize the familiar, generalize to the similar, and adapt to the novel. *Psychological Review*. 2015; 122(2):148–203. doi: 10.1037/a0038695. [PubMed: 25844873]
- Knill DC, Pouget A. The Bayesian brain: the role of uncertainty in neural coding and computation. *Trends in Neurosciences*. 2004; 27(12):712–719. doi: 10.1016/J.Tins.2004.10.007. [PubMed: 15541511]
- Knoeferle P, Crocker MW, Scheepers C, Pickering MJ. The influence of the immediate visual context on incremental thematic role-assignment: evidence from eye-movements in depicted events. *Cognition*. 2005; 95(1):95–127. doi: 10.1016/j.cognition.2004.03.002. [PubMed: 15629475]
- Kolk HHJ, Chwilla DJ, van Herten M, Oor PJ. Structure and limited capacity in verbal working memory: A study with event-related potentials. *Brain and Language*. 2003; 85(1):1–36. doi: 10.1016/S0093-934X(02)00548-5. [PubMed: 12681346]
- Kruschke JK. Bayesian approaches to associative learning: From passive to active learning. *Learning and Behavior*. 2008; 36(3):210–226. doi: 10.3758/lb.36.3.210. [PubMed: 18683466]
- Kuhl PK. Human adults and human infants show a “perceptual magnet effect” for the prototypes of speech categories, monkeys do not. *Perception and Psychophysics*. 1991; 50(2):93–107. doi: 10.3758/bf03212211. [PubMed: 1945741]
- Kuperberg GR. Neural mechanisms of language comprehension: Challenges to syntax. *Brain Research*. 2007; 1146:23–49. doi: 10.1016/j.brainres.2006.12.063. [PubMed: 17400197]
- Kuperberg, GR. The proactive comprehender: What event-related potentials tell us about the dynamics of reading comprehension. In: Miller, B.; Cutting, L.; McCardle, P., editors. *Unraveling Reading Comprehension: Behavioral, Neurobiological, and Genetic Components*. Paul Brookes Publishing; Baltimore, MD: 2013. p. 176-192.
- Kuperberg, GR. What event-related potentials might tell us about the neural architecture of language comprehension. under review
- Kuperberg GR, Paczynski M, Ditman T. Establishing causal coherence across sentences: an ERP study. *Journal of Cognitive Neuroscience*. 2011; 23(5):1230–1246. doi: 10.1162/jocn.2010.21452. [PubMed: 20175676]
- Kuperberg GR, Sitnikova T, Caplan D, Holcomb PJ. Electrophysiological distinctions in processing conceptual relationships within simple sentences. *Cognitive Brain Research*. 2003; 17(1):117–129. doi: 10.1016/S0926-6410(03)00086-7. [PubMed: 12763198]
- Kurumada C, Brown M, Bibyk S, Pontillo DF, Tanenhaus MK. Is it or isn't it: Listeners make rapid use of prosody to infer speaker meanings. *Cognition*. 2014; 133(2):335–342. doi: 10.1016/j.cognition.2014.05.017. [PubMed: 25128792]
- Kutas, M.; DeLong, KA.; Smith, NJ. A look around at what lies ahead: Prediction and predictability in language processing. In: Bar, M., editor. *Predictions in the brain: Using our past to generate a future*. Oxford University Press; 2011. p. 190-207.
- Kutas M, Federmeier KD. Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology*. 2011; 62:621–647. doi: 10.1146/annurev.psych.093008.131123.

- Kutas M, Hillyard SA. Reading senseless sentences: brain potentials reflect semantic incongruity. *Science*. 1980; 207(4427):203–205. doi: 10.1126/science.7350657. [PubMed: 7350657]
- Kutas M, Hillyard SA. Brain potentials during reading reflect word expectancy and semantic association. *Nature*. 1984; 307(5947):161–163. doi: 10.1038/307161a0. [PubMed: 6690995]
- Kwiatkowski, T.; Goldwater, S.; Zettlemoyer, L.; Steedman, M. A probabilistic model of syntactic and semantic acquisition from child-directed utterances and their meanings. Paper presented at the 13th Conference of the European Chapter of the Association for Computational Linguistics; Avignon, France. 2012.
- Labov W. Contraction, deletion, and inherent variability of the English copula. *Language*. 1969; 45(4): 715–762. doi: 10.2307/412333.
- Landauer TK, Dumais ST. A solution to Plato's problem: The Latent Semantic Analysis theory of acquisition, induction, and representation of knowledge. *Psychological Review*. 1997; 104(2): 211–240. doi: 10.1037/0033-295x.104.2.211.
- Landauer TK, Foltz PW, Laham D. An introduction to Latent Semantic Analysis. *Discourse Processes*. 1998; 25(2-3):259–284. doi: 10.1080/01638539809545028.
- Lau EF, Holcomb PJ, Kuperberg GR. Dissociating N400 effects of prediction from association in single-word contexts. *Journal of Cognitive Neuroscience*. 2013; 25(3):484–502. doi: 10.1162/jocn\_a\_00328. [PubMed: 23163410]
- Lau EF, Phillips C, Poeppel D. A cortical network for semantics: (De)constructing the N400. *Nature Reviews Neuroscience*. 2008; 9(12):920–933. doi: 10.1038/nrn2532.
- Laughlin SB, de Ruyter van Steveninck RR, Anderson JC. The metabolic cost of neural information. *Nature Neuroscience*. 1998; 1(1):36–41. doi: 10.1038/236. [PubMed: 10195106]
- Levinson, SC. Action formation and ascription. In: Stivers, T.; Sidnell, J., editors. *The Handbook of Conversation Analysis*. Wiley-Blackwell; Malden, MA: 2013. p. 103-130.
- Levy, R. Probabilistic Models of Word Order and Syntactic Discontinuity. Stanford University; 2005. PhD Dissertation
- Levy R. Expectation-based syntactic comprehension. *Cognition*. 2008; 106(3):1126–1177. doi: 10.1016/j.cognition.2007.05.006. [PubMed: 17662975]
- Levy R, Bicknell K, Slattery T, Rayner K. Eye movement evidence that readers maintain and act on uncertainty about past linguistic input. *Proceedings of the National Academy of Sciences, USA*. 2009; 106(50):21086–21090. doi: 10.1073/pnas.0907664106.
- Lewis A, Bastiaansen M. A predictive coding framework for rapid neural dynamics during sentence-level language comprehension. *Cortex*. 2015; 68:155–168. doi: 10.1016/j.cortex.2015.02.014. [PubMed: 25840879]
- Lewis RL. Falsifying serial and parallel parsing models: Empirical conundrums and an overlooked paradigm. *Journal of Psycholinguistic Research*. 2000; 29(2):241–248. doi: 10.1023/a:1005105414238. [PubMed: 10709188]
- Lewis RL, Howes A, Singh S. Computational rationality: linking mechanism and behavior through bounded utility maximization. *Topics in Cognitive Science*. 2014; 6(2):279–311. doi: 10.1111/tops.12086. [PubMed: 24648415]
- Lewis RL, Shvartsman M, Singh S. The adaptive nature of eye movements in linguistic tasks: how payoff and architecture shape speed-accuracy trade-offs. *Topics in Cognitive Science*. 2013; 5(3): 581–610. doi: 10.1111/tops.12032. [PubMed: 23757203]
- Linzen T, Jaeger TF. Uncertainty and expectation in sentence processing: evidence from subcategorization distributions. *Cognitive Science*. in press. doi: 10.1111/cogs.12274.
- Luck, SJ. *An Introduction to the Event-Related Potential Technique*. 2nd. MIT Press; Cambridge, MA: 2014.
- MacDonald MC, Just MA, Carpenter PA. Working memory constraints on the processing of syntactic ambiguity. *Cognitive Psychology*. 1992; 24(1):56–98. doi: 10.1016/0010-0285(92)90003-k. [PubMed: 1537232]
- MacDonald MC, Pearlmutter NJ, Seidenberg MS. The lexical nature of syntactic ambiguity resolution. *Psychological Review*. 1994; 101(4):676–703. doi: 10.1037/0033-295X.101.4.676. [PubMed: 7984711]

- MacKay, DJC. *Information Theory, Inference, and Learning Algorithms*. Vol. 7. Cambridge University Press; Cambridge, UK: 2003.
- Magyari L, de Ruiter JP. Prediction of turn-ends based on anticipation of upcoming words. *Frontiers in Psychology*. 2012; 3:376. doi: 10.3389/fpsyg.2012.00376. [PubMed: 23112776]
- Marr, D. *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information*. Freeman; New York: 1982.
- Marslen-Wilson WD. Functional parallelism in spoken word-recognition. *Cognition*. 1987; 25:71–102. doi: 10.1016/0010-0277(87)90005-9. [PubMed: 3581730]
- Marslen-Wilson WD, Brown C, Tyler LK. Lexical representations in spoken language comprehension. *Language and Cognitive Processes*. 1988; 3:1–17. doi: 10.1080/01690968808402079.
- Massaro DW. Testing between the TRACE model and the fuzzy logical model of speech perception. *Cognitive Psychology*. 1989; 21(3):398–421. doi: 10.1016/0010-0285(89)90014-5. [PubMed: 2758786]
- Matsuki K, Chow T, Hare M, Elman JL, Scheepers C, McRae K. Event-based plausibility immediately influences on-line language comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2011; 37(4):913–934. doi: 10.1037/a0022964.
- McCarthy G, Nobre AC. Modulation of semantic processing by spatial selective attention. *Electroencephalography and Clinical Neurophysiology*. 1993; 88(3):210–219. doi: 10.1016/0168-5597(93)90005-a. [PubMed: 7684969]
- McClelland, JL. Connectionist models and Bayesian inference. In: Oaksford, M.; Chater, N., editors. *Rational Models of Cognition*. Oxford University Press; New York: 1998. p. 21–52.
- McClelland JL. Integrating probabilistic models of perception and interactive neural networks: a historical and tutorial review. *Frontiers in Psychology*. 2013; 4:503. doi: 10.3389/fpsyg.2013.00503. [PubMed: 23970868]
- McClelland JL, Elman JL. The TRACE model of speech perception. *Cognitive Psychology*. 1986; 18(1):1–86. doi: 10.1016/0010-0285(86)90015-0. [PubMed: 3753912]
- McClelland JL, O'Regan JK. Expectations increase the benefit derived from parafoveal visual information in reading words aloud. *Journal of Experimental Psychology: Human Perception and Performance*. 1981; 7(3):634–644. doi: 10.1037/0096-1523.7.3.634.
- McClelland JL, Rumelhart DE. An interactive activation model of context effects in letter perception: I. An account of basic findings. *Psychological Review*. 1981; 88(5):375–407. doi: 10.1037//0033-295x.88.5.375.
- McClelland JL, St. John M, Taraban R. Sentence comprehension: A parallel distributed processing approach. *Language and Cognitive Processes*. 1989; 4:287–336.
- McDonald SA, Shillcock RC. Eye movements reveal the on-line computation of lexical probabilities during reading. *Psychological Science*. 2003; 14(6):648–652. [PubMed: 14629701]
- McGowan KB. Social expectation improves speech perception in noise. *Language and Speech*. 2015 doi: 10.1177/0023830914565191.
- McKoon G, Ratcliff R. Inference during reading. *Psychological Review*. 1992; 99(3):440–466. doi: 10.1037/0033-295X.99.3.440. [PubMed: 1502273]
- McRae K, Ferretti TR, Amyote L. Thematic roles as verb-specific concepts. *Language and Cognitive Processes*. 1997; 12(2-3):137–176. doi: 10.1080/016909697386835.
- McRae K, Matsuki K. People use their knowledge of common events to understand language, and do so as quickly as possible. *Language and Linguistics Compass*. 2009; 3(6):1417–1429. doi: 10.1111/j.1749-818X.2009.00174.x. [PubMed: 22125574]
- Metusalem R, Kutas M, Urbach TP, Hare M, McRae K, Elman JL. Generalized event knowledge activation during online sentence comprehension. *Journal of Memory and Language*. 2012; 66(4):545–567. doi: 10.1016/j.jml.2012.01.001. [PubMed: 22711976]
- Miller GA, Heise GA, Lichten W. The intelligibility of speech as a function of the context of the test materials. *Journal of Experimental Psychology*. 1951; 41(5):329–335. doi: 10.1037/h0062491. [PubMed: 14861384]
- Morton J. Interaction of information in word recognition. *Psychological Review*. 1969; 76(2):165–178. doi: 10.1037/h0027366.

- Myers JL, O'Brien EJ. Accessing the discourse representation during reading. *Discourse Processes*. 1998; 26(2&3):131–157. doi: 10.1080/01638539809545042.
- Narayanan, S.; Jurafsky, D. Combining structure and probabilities in a Bayesian model of human sentence processing. Paper presented at the CUNY Conference on Human Sentence Processing; New York. 2002.
- Neely, JH. Semantic priming effects in visual word recognition: A selective review of current findings and theories. In: Besner, D.; Humphreys, GW., editors. *Basic Processes in Reading and Visual Word Recognition*. Erlbaum; Hillsdale, NJ: 1991. p. 264-333.
- Neely JH, Keefe DE, Ross K. Semantic priming in the lexical decision task: Roles of prospective prime-generated expectancies and retrospective semantic matching. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 1989; 15(6):1003–1019. doi: 10.1037/0278-7393.15.6.1003.
- Niedzielski N. The effect of social information on the perception of sociolinguistic variables. *Journal of Language and Social Psychology*. 1999; 18(1):62–85. doi: 10.1177/0261927x99018001005.
- Norris D. Shortlist: a connectionist model of continuous speech recognition. *Cognition*. 1994; 52(3): 189–234. doi: 10.1016/0010-0277(94)90043-4.
- Norris D. The Bayesian reader: explaining word recognition as an optimal Bayesian decision process. *Psychological Review*. 2006; 113(2):327–357. doi: 10.1037/0033-295X.113.2.327. [PubMed: 16637764]
- Norris D, McQueen JM. Shortlist B: a Bayesian model of continuous speech recognition. *Psychological Review*. 2008; 115(2):357–395. doi: 10.1037/0033-295X.115.2.357. [PubMed: 18426294]
- Norris D, McQueen JM, Cutler A. Merging information in speech recognition: Feedback is never necessary. *Behavioral and Brain Sciences*. 2000; 23(3):299. +. doi: 10.1017/S0140525x00003241. [PubMed: 11301575]
- Otten M, Van Berkum JJA. What makes a discourse constraining? Comparing the effects of discourse message and scenario fit on the discourse-dependent N400 effect. *Brain Research*. 2007; 1146:158–171. doi: 10.1016/j.brainres.2007.03.058. [PubMed: 16916496]
- Paczynski M, Kuperberg GR. Electrophysiological evidence for use of the animacy hierarchy, but not thematic role assignment, during verb argument processing. *Language and Cognitive Processes*. 2011; 26(9):1402–1456. doi: 10.1080/01690965.2011.580143. [PubMed: 22199415]
- Paczynski M, Kuperberg GR. Multiple influences of semantic memory on sentence processing: Distinct effects of semantic relatedness on violations of real-world event/state knowledge and animacy selection restrictions. *Journal of Memory and Language*. 2012; 67(4):426–448. doi: 10.1016/j.jml.2012.07.003. [PubMed: 23284226]
- Perfors A, Tenenbaum JB, Griffiths TL, Xu F. A tutorial introduction to Bayesian models of cognitive development. *Cognition*. 2011; 120(3):302–321. doi: 10.1016/j.cognition.2010.11.015. [PubMed: 21269608]
- Pickering MJ, Garrod S. Do people use language production to make predictions during comprehension? *Trends in Cognitive Sciences*. 2007; 11(3):105–110. doi: 10.1016/j.tics.2006.12.002. [PubMed: 17254833]
- Pickering MJ, Garrod S. An integrated theory of language production and comprehension. *Behavioral and Brain Sciences*. 2013; 36(04):329–347. doi: 10.1017/S0140525X12001495. [PubMed: 23789620]
- Posner, MI.; Snyder, CRR. Attention and cognitive control. In: Solso, RL., editor. *Information Processing and Cognition: the Loyola Symposium*; Hillsdale, NJ: Lawrence Erlbaum Associates; 1975. p. 55-85.
- Pykkönen P, Järvikivi J. Activation and persistence of implicit causality information in spoken language comprehension. *Experimental Psychology*. 2010 doi: 10.1027/1618-3169/a000002.
- Qian, T.; Jaeger, TF. Topic shift in efficient discourse production. In: Carlson, L.; Holscher, C.; Shipley, T., editors. *Proceedings of the 33rd Annual Conference of the Cognitive Science Society*; Boston, MA: Cognitive Science Society; 2011. p. 3313-3318.

- Qian T, Jaeger TF, Aslin RN. Learning to represent a multi-context environment: more than detecting changes. *Frontiers in Psychology*. 2012; 3:228. doi: 10.3389/fpsyg.2012.00228. [PubMed: 22833727]
- Rabovsky M, McRae K. Simulating the N400 ERP component as semantic network error: Insights from a feature-based connectionist attractor model of word meaning. *Cognition*. 2014; 132(1): 68–89. doi: 10.1016/j.cognition.2014.03.010. [PubMed: 24762924]
- Rao RP, Ballard DH. Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects. *Nature Neuroscience*. 1999; 2(1):79–87. doi: 10.1038/4580. [PubMed: 10195184]
- Rayner K, Binder KS, Ashby J, Pollatsek A. Eye movement control in reading: word predictability has little influence on initial landing positions in words. *Vision Research*. 2001; 41(7):943–954. doi: 10.1016/s0042-6989(00)00310-2. [PubMed: 11248279]
- Rayner K, Well AD. Effects of contextual constraint on eye movements in reading: A further examination. *Psychonomic Bulletin and Review*. 1996; 3(4):504–509. doi: 10.3758/BF03214555. [PubMed: 24213985]
- Rescorla, RA.; Wagner, AR. A theory of Pavlovian conditioning: Variations in the effectiveness of reinforcement and nonreinforcement. In: Prokasy, WE.; Black, AH., editors. *Classical conditioning II: Current research and theory*. Appleton-Century-Crofts; New York: 1972. p. 64-99.
- Roark, B.; Bachrach, A.; Cardenas, C.; Pallier, C. Deriving lexical and syntactic expectation-based measures for psycholinguistic modeling via incremental top-down parsing. Paper presented at the Proceedings of the 2009 Conference on Empirical Methods in Natural Language Processing (EMNLP '09); Singapore. 2009.
- Rohde H, Horton WS. Anticipatory looks reveal expectations about discourse relations. *Cognition*. 2014; 133(3):667–691. doi: 10.1016/j.cognition.2014.08.012. [PubMed: 25247235]
- Rohde H, Levy R, Kehler A. Anticipating explanations in relative clause processing. *Cognition*. 2011; 118(3):339–358. doi: 10.1016/j.cognition.2010.10.016. [PubMed: 21216396]
- Rumelhart DE, McClelland JL. An interactive activation model of context effects in letter perception: II. The contextual enhancement effect and some tests and extensions of the model. *Psychological Review*. 1982; 89(1):60–94. doi: 10.1037/0033-295x.89.1.60. [PubMed: 7058229]
- Sacks H, Schegloff EA, Jefferson G. A simplest systematics for the organization of turn-taking for conversation. *Language*. 1974; 50(4):696–735. doi: 10.2307/412243.
- Salverda AP, Brown M, Tanenhaus MK. A goal-based perspective on eye movements in visual world studies. *Acta Psychologica*. 2011; 137(2):172–180. doi: 10.1016/j.actpsy.2010.09.010. [PubMed: 21067708]
- Sanford, AJ. On the nature of text-driven inference. In: Balota, DA.; d'Arcais, F.; Rayner, K., editors. *Comprehension processes in reading*. Erlbaum; Hillsdale, NJ: 1990.
- Sanford AJ, Garrod SC. The role of scenario mapping in text comprehension. *Discourse Processes*. 1998; 26(2-3):159–190. doi: 10.1080/01638539809545043.
- Schank, RC.; Abelson, RP. *Scripts, Plans, Goals, and Understanding: An Inquiry Into Human Knowledge Structures*. Lawrence Erlbaum Associates; Hillsdale, NJ: 1977.
- Schwanenflugel PJ, Lacount KL. Semantic relatedness and the scope of facilitation for upcoming words in sentences. *Journal of Experimental Psychology: Learning Memory and Cognition*. 1988; 14(2):344–354. doi: 10.1037//0278-7393.14.2.344.
- Schwanenflugel PJ, Shoben EJ. The influence of sentence constraint on the scope of facilitation for upcoming words. *Journal of Memory and Language*. 1985; 24:232–252. doi: 10.1016/0749-596X(85)90026-9.
- Sedivy JC, Tanenhaus MK, Chambers CG, Carlson GN. Achieving incremental semantic interpretation through contextual representation. *Cognition*. 1999; 71(2):109–147. doi: 10.1016/s0010-0277(99)00025-6. [PubMed: 10444906]
- Shadlen MN, Newsome WT. Noise, neural codes and cortical organization. *Current Opinion in Neurobiology*. 1994; 4(4):569–579. doi: 10.1016/0959-4388(94)90059-0. [PubMed: 7812147]
- Shannon CE. A mathematical theory of communication. *Bell System Technical Journal*. 1948; 27(3): 379–423. doi: 10.1002/j.1538-7305.1948.tb01338.x.

- Simon HA. Rational choice and the structure of the environment. *Psychological Review*. 1956; 63(2): 129–138. doi: 10.1037/h0042769. [PubMed: 13310708]
- Simon HA. Invariants of human behavior. *Annual Review of Psychology*. 1990; 41:1–19. doi: 10.1146/annurev.ps.41.020190.000245.
- Sitnikova, T.; Holcomb, P.; Kuperberg, GR. Neurocognitive mechanisms of human comprehension. In: Shipley, TF.; Zacks, JM., editors. *Understanding Events: How Humans See, Represent, and Act on Events*. Oxford University Press; 2008. p. 639–683.
- Smith NJ, Levy R. The effect of word predictability on reading time is logarithmic. *Cognition*. 2013; 128(3):302–319. doi: 10.1016/j.cognition.2013.02.013. [PubMed: 23747651]
- Snedeker J, Yuan S. Effects of prosodic and lexical constraints on parsing in young children (and adults). *Journal of Memory and Language*. 2008; 58(2):574–608. doi: 10.1016/j.jml.2007.08.001. [PubMed: 19190721]
- Sohoglu E, Peelle JE, Carlyon RP, Davis MH. Predictive top-down integration of prior knowledge during speech perception. *Journal of Neuroscience*. 2012; 32(25):8443–8453. doi: 10.1523/JNEUROSCI.5069-11.2012. [PubMed: 22723684]
- Sonderegger, M.; Yu, A. A rational account of perceptual compensation for coarticulation. In: Ohlsson, S.; Camtrabone, R., editors. *Proceedings of the 32nd Annual Conference of the Cognitive Science Society*; Portland, OR: Cognitive Science Society; 2010. p. 375–380.
- Spivey-Knowlton MJ, Trueswell JC, Tanenhaus MK. Context effects in syntactic ambiguity resolution: Discourse and semantic influences in parsing reduced relative clauses. *Canadian Journal of Experimental Psychology*. 1993; 47(2):276–309. doi: 10.1037/h0078826. [PubMed: 8364532]
- Stanovich KE, West RF. Mechanisms of sentence context effects in reading: Automatic activation and conscious attention. *Memory and Cognition*. 1979; 7:77–85. doi: 10.3758/BF03197588.
- Stanovich KE, West RF. The effect of a sentence context on ongoing word recognition: Tests of a two-process theory. *Journal of Experimental Psychology: Human Perception and Performance*. 1981; 7:658–772. doi: 10.1037/0096-1523.7.3.658.
- Stanovich KE, West RF. On priming by a sentence context. *Journal of Experimental Psychology: General*. 1983; 112(1):1–36. doi: 10.1037/0096-3445.112.1.1. [PubMed: 6221061]
- Staub A. The effect of lexical predictability on eye movements in reading: critical review and theoretical interpretation. *Language and Linguistics Compass*. 2015; 9(8):311–327. doi: 10.1111/lnc3.12151.
- Staub A, Grant M, Astheimer L, Cohen A. The influence of cloze probability and item constraint on cloze task response time. *Journal of Memory and Language*. 2015; 82:1–17. doi: 10.1016/j.jml.2015.02.004.
- Stilp CE, Kluender KR. Cochlea-scaled entropy, not consonants, vowels, or time, best predicts speech intelligibility. *Proceedings of the National Academy of Sciences of the United States of America*. 2010; 107(27):12387–12392. doi: 10.1073/pnas.0913625107. [PubMed: 20566842]
- Stivers T, Enfield NJ, Brown P, Englert C, Hayashi M, Heinemann T, Levinson SC. Universals and cultural variation in turn-taking in conversation. *Proceedings of the National Academy of Sciences*. 2009; 106(26):10587–10592. doi: 10.1073/pnas.0903616106.
- Sussman, RS. Processing and representation of verbs: Insights from instruments. University of Rochester; 2006. Ph.D. Doctoral dissertation
- Swinney DA. Lexical access during sentence comprehension:(Re) consideration of context effects. *Journal of Verbal Learning and Verbal Behavior*. 1979; 18(6):645–659. doi: 10.1016/S0022-5371(79)90355-4.
- Szostak CM, Pitt MA. The prolonged influence of subsequent context on spoken word recognition. *Attention, Perception & Psychophysics*. 2013; 75(7):1533–1546. doi: 10.3758/s13414-013-0492-3.
- Tanenhaus MK, Brown-Schmidt S. Language processing in the natural world. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*. 2008; 363(1493):1105–1122. doi: 10.1098/rstb.2007.2162. [PubMed: 17895223]
- Tanenhaus, MK.; Chambers, CG.; Hanna, JE. Referential domains in spoken language comprehension: Using eye movements to bridge the product and action traditions. In: Henderson, JM.; Ferreira,



- F., editors. *The Interface of Language, Vision, and Action: Eye Movements and the Visual World*. Psychology Press; New York: 2004. p. 279-317.
- Tanenhaus MK, Spivey-Knowlton MJ, Eberhard KM, Sedivy JC. Integration of visual and linguistic information in spoken language comprehension. *Science*. 1995; 268(5217):1632–1634. doi: 10.1126/science.7777863. [PubMed: 7777863]
- Tanenhaus, MK.; Trueswell, JC. Sentence comprehension. In: Miller, JL.; Eimas, PD., editors. *Speech, Language, and Communication*. 2. Vol. 11. Academic Press; San Diego, CA: 1995. p. 217-262.
- Tanenhaus, MK.; Trueswell, JC. Eye movements and spoken language comprehension. In: Traxler, MJ.; Gernsbacher, MA., editors. *Handbook of Psycholinguistics*. 2. Oxford University Press; Oxford: 2006. p. 863-900.
- Taylor W. 'Cloze' procedure: A new tool for measuring readability. *Journalism Quarterly*. 1953; 30:415–433.
- Tooley KM, Traxler MJ. Syntactic priming effects in comprehension: a critical review. *Language and Linguistics Compass*. 2010; 4(10):925–937. doi: 10.1111/j.1749-818X.2010.00249.x.
- Traxler MJ. Trends in syntactic parsing: anticipation, Bayesian estimation, and good-enough parsing. *Trends in Cognitive Sciences*. 2014; 18(11):605–611. doi: 10.1016/j.tics.2014.08.001. [PubMed: 25200381]
- Traxler MJ, Foss DJ. Effects of sentence constraint on priming in natural language comprehension. *Journal of Experimental Psychology: Learning, Memory and Cognition*. 2000; 26(5):1266–1282. doi: 10.1037/0278-7393.26.5.1266.
- Traxler MJ, Pickering MJ, Clifton C. Adjunct attachment is not a form of lexical ambiguity resolution. *Journal of Memory and Language*. 1998; 39(4):558–592. doi: 10.1006/jmla.1998.2600.
- Trueswell JC, Tanenhaus MK, Garnsey SM. Semantic influences on parsing: Use of thematic role information in syntactic ambiguity resolution. *Journal of Memory and Language*. 1994; 33:285–318. doi: 10.1006/jmla.1994.1014.
- Trueswell JC, Tanenhaus MK, Kello C. Verb-specific constraints in sentence processing: Separating effects of lexical preference from garden-paths. *Journal of Experimental Psychology: Learning, Memory and Cognition*. 1993; 19(3):528–553. doi: 10.1037/0278-7393.19.3.528.
- Van Berkum JJA, Brown CM, Zwitserlood P, Kooijman V, Hagoort P. Anticipating upcoming words in discourse: evidence from ERPs and reading times. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2005; 31(3):443–467. doi: 10.1037/0278-7393.31.3.443.
- van den Broek P, Lorch RF, Linderholm T, Gustafson M. The effects of readers' goals on inference generation and memory for texts. *Memory and Cognition*. 2001; 29(8):1081–1087. doi: 10.3758/bf03206376. [PubMed: 11913743]
- Van Dijk, TA.; Kintsch, W. *Strategies of Discourse Comprehension*. Academic Press; New York: 1983.
- van Gompel RPG, Pickering MJ, Pearson J, Liversedge SP. Evidence against competition during syntactic ambiguity resolution. *Journal of Memory and Language*. 2005; 52(2):284–307. doi: 10.1016/j.jml.2004.11.003.
- van Gompel RPG, Pickering MJ, Traxler MJ. Reanalysis in sentence processing: Evidence against current constraint-based and two-stage models. *Journal of Memory and Language*. 2001; 45(2): 225–258. doi: 10.1006/jmla.2001.2773.
- Van Petten C, Luka BJ. Prediction during language comprehension: benefits, costs, and ERP components. *International Journal of Psychophysiology*. 2012; 83(2):176–190. doi: 10.1016/j.ijpsycho.2011.09.015. [PubMed: 22019481]
- Wacongne C, Labyt E, van Wassenhove V, Bekinschtein T, Naccache L, Dehaene S. Evidence for a hierarchy of predictions and prediction errors in human cortex. *Proceedings of the National Academy of Sciences*. 2011; 108(51):20754–20759. doi: 10.1073/Pnas.1117807108.
- Warren RM. Perceptual restoration of missing speech sounds. *Science*. 1970; 167(3917):392–393. doi: 10.1126/science.167.3917.392. [PubMed: 5409744]
- Weiss S, Mueller HM. "Too many betas do not spoil the broth": The role of beta brain oscillations in language processing. *Frontiers in Psychology*. 2012; 3:201. doi: 10.3389/fpsyg.2012.00201. [PubMed: 22737138]
- Wicha NY, Moreno EM, Kutas M. Anticipating words and their gender: An event-related brain potential study of semantic integration, gender expectancy, and gender agreement in Spanish

- sentence reading. *Journal of Cognitive Neuroscience*. 2004; 16(7):1272–1288. doi: 10.1162/0898929041920487. [PubMed: 15453979]
- Wilson MP, Garnsey SM. Making simple sentences hard: Verb bias effects in simple direct object sentences. *Journal of Memory and Language*. 2009; 60(3):368–392. doi: 10.1016/j.jml.2008.09.005. [PubMed: 20160997]
- Wlotko EW, Federmeier K. Time for prediction? The effect of presentation rate on predictive sentence comprehension during word-by-word reading. *Cortex*. 2015; 68:20–32. doi: 10.1016/j.cortex.2015.03.014. [PubMed: 25987437]
- Wlotko EW, Federmeier KD. So that's what you meant! Event-related potentials reveal multiple aspects of context use during construction of message-level meaning. *NeuroImage*. 2012; 62(1):356–366. doi: 10.1016/j.neuroimage.2012.04.054. [PubMed: 22565202]
- Wood JN, Grafman J. Human prefrontal cortex: processing and representational perspectives. *Nature Reviews Neuroscience*. 2003; 4(2):139–147. doi: 10.1038/Nrn1033. [PubMed: 12563285]
- Woods DL, Yund EW, Herron TJ, Ua Cruadhlaich MA. Consonant identification in consonant-vowel-consonant syllables in speech-spectrum noise. *The Journal of the Acoustical Society of America*. 2010; 127(3):1609–1623. doi: 10.1121/1.3293005. [PubMed: 20329860]
- Wu, S.; Bachrach, A.; Cardenas, C.; Schuler, C. Complexity metrics in an incremental right-corner parser. Paper presented at the Proceedings of the 48th Annual Meeting of the Association for Computational Linguistics (ACL '10); Uppsala, Sweden. 2010.
- Xiang M, Kuperberg GR. Reversing expectations during discourse comprehension. *Language, Cognition and Neuroscience*. 2015; 30(6):648–672. doi: 10.1080/23273798.2014.995679.
- Yoon SO, Koh S, Brown-Schmidt S. Influence of perspective and goals on reference production in conversation. *Psychonomic Bulletin and Review*. 2012; 19(4):699–707. doi: 10.3758/s13423-012-0262-6. [PubMed: 22572985]
- Zwaan RA, Radvansky GA. Situation models in language comprehension and memory. *Psychological Bulletin*. 1998; 123(2):162–185. doi: 10.1037/0033-2909.123.2.162. [PubMed: 9522683]