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The real-time prediction and inhibition of linguistic outcomes: Effects of language and literacy skill

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ABSTRACT

Recent studies have found considerable individual variation in language comprehenders' predictive behaviors, as revealed by their anticipatory eye movements during language comprehension. The current study investigated the relationship between these predictive behaviors and the language and literacy skills of a diverse, community-based sample of young adults. We found that rapid automatized naming (RAN) was a key determinant of comprehenders' prediction ability (e.g., as reflected in predictive eye movements to a WHITE CAKE on hearing "The boy will eat the white…"). Simultaneously, comprehension-based measures predicted participants' ability to inhibit eye movements to objects that shared features with predictable referents but were implausible completions (e.g., as reflected in eye movements to a white but inedible WHITE CAR). These findings suggest that the excitatory and inhibitory mechanisms that support prediction during language processing are closely linked with specific cognitive abilities that support literacy. We show that a self-organizing cognitive architecture captures this pattern of results.

1. Introduction

Prediction is widely documented across studies of language comprehension (e.g., Altmann & Kamide, 1999; DeLong, Urbach, & Kutas, 2005) and figures prominently in theoretical approaches to language processing (e.g., Dell & Chang, 2014; Elman, 1990; Federmeier, 2007; Levy, 2008; Pickering & Garrod, 2013, 2014). Prior work indicates that language comprehenders are able to generate expectations about future linguistic input and outcomes, and launch predictive behaviors (e.g., eye movements) on the basis of these expectations. In the current study, we investigated individual differences in these behaviors, and their relationship with comprehenders' language and literacy skills. Our aims were threefold: (1) to examine predictive behaviors across a range of the skill continuum; (2) to explore potential determinants of comprehenders' prediction ability, including differences in the activation and inhibition of linguistic outcomes; and (3) to examine the cognitive mechanisms that support prediction. We investigated these questions in a diverse, community-based sample of young adults with considerable variation in their language and literacy skills, as determined through an extensive battery of cognitive measures.

Influences of predictability on language comprehension have long been recognized. For example, Rayner and Well (1996; see also Ehrlich & Rayner, 1981; Smith & Levy, 2013) found that comprehenders read a word like "contents," a high probability completion of "The postman opened the package to inspect its…," faster in this context than a word like "packing," a low probability completion. Thus, comprehenders more readily activated more predictable words. In a closely related study using event-related potentials, DeLong et al. (2005) found that when high and low probability sentence completions differed in their articles (e.g., "The day was breezy so the boy went outside to fly a kite/an airplane"), low probability articles (i.e., "an," preceding the low probability noun completion, "airplane") elicited a larger N400 component, typical of semantic anomalies, than high probability articles.

The visual world paradigm (Cooper, 1974; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995), in which listeners hear spoken language about a visual display, has also been used to study prediction in language comprehension. Altmann and Kamide (1999) showed that listeners hearing "The boy will eat…," while viewing a scene with a CAKE and various inedible objects launched eye movements to the CAKE upon hearing "eat." Thus, comprehenders were able to pre-activate CAKE, and pre-orient their attention to it, on the basis of the verb *eat*'s selectional restrictions before "cake" was explicitly referred to. Similar effects have been reported across a range of visual world studies (for a review see Kamide, 2008), and across a range of ages

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(2-year-olds: Mani & Huettig, 2012; 6-year-olds: Nation, Marshall, & Altmann, 2003; 3- to 10-year-olds: Borovsky, Elman, & Fernald, 2012; adolescents: Borovsky, Burns, Elman, & Evans, 2013). Moreover, these predictive behaviors have been hypothesized to play a critical role in real-time processing (e.g., Levy, 2008), learning (e.g., Elman, 1990), and production (e.g., Dell & Chang, 2014; Pickering & Garrod, 2013, 2014).

More recently, considerable variation in comprehenders' predictive eye movements has been observed in the visual world paradigm. Mani and Huettig (2012) found that 2-year-olds, like adults (e.g., Almann & Kamide, 1999), launched more eye movements to a CAKE when hearing "The boy eats the big…" than "The boy sees the big…". However, children's prediction ability was positively correlated with their productive vocabulary size. Alternatively, Borovsky et al. (2012) found that comprehenders' prediction ability was positively correlated with their receptive vocabulary size, a pattern observed in both adults and younger comprehenders. Relatedly, Mani and Huettig (2014) found that 8-year-olds' prediction ability was positively correlated with a particular aspect of literacy: word, but not pseudo-word, reading. Finally, Mishra, Singh, Pandey, and Huettig (2012) observed an even more dramatic pattern among high and low literates: while they found clear evidence for prediction in high literates, they found no evidence for prediction in the eye movement patterns of low literates.

Individual differences in predictive behaviors have also been observed during reading (e.g., Ashby, Rayner, & Clifton, 2005) and have been linked to learning outcomes (e.g., Karuza, Farmer, Fine, Smith, & Jaeger, 2014; Misyak, Christiansen, & Tomblin, 2010). Taken together, these results support a close link between prediction-driven behaviors and measures of language and literacy skill, such that skilled individuals are better able to generate expectations about future linguistic input and outcomes, and launch predictive eye movements on the basis of these expectations.

A variety of claims have been made about the source of these individual differences in comprehenders' predictive behaviors. Huettig and colleagues (Mani & Huettig, 2012, 2014; Mishra et al., 2012) have highlighted various links: for example, Mishra et al. surmise that accumulation of reading experience may "fine-tune" processes that are involved in prediction. Specifically, reading development may boost comprehenders' *knowledge* (e.g., of statistics that are predictive of linguistic outcomes) and/or their *speed of processing* (e.g., allowing them to make gains in reading fluency) in ways that bear on prediction. However, Mishra et al. did not assess these abilities of their participants, so their data speak only indirectly to these hypotheses. Relatedly, Mani and Huettig (2014) argue that the acquisition of orthographic representations across reading development may "sharpen" comprehenders' lexical representations, enabling faster retrieval of lexical information to support prediction (see also Perfetti & Hart, 2002). Finally, Mani and Huettig (2012) argue that individual differences in prediction may stem from variability specific to comprehenders' production skill (e.g., as reflected in their productive vocabulary size), consistent with the claim that prediction depends on processes integral to production (e.g., Dell & Chang, 2014; Pickering & Garrod, 2013, 2014).

Alternatively, capacity-based approaches (e.g., Just & Carpenter, 1992) have classically linked comprehenders' performance in various aspects of sentence processing to working memory capacity. This approach assumes that comprehenders have a limited pool of working memory resources available to support processing. Individual differences are assumed to stem from variability in the size of comprehenders' pools of resources; comprehenders with more resources are better able to support processing than comprehenders with fewer resources. Consistent with this view, measures of working memory capacity (e.g., sentence span; Daneman & Carpenter, 1980) have been shown to correlate with various aspects of performance. Similarly, an alternative explanation of the patterns observed by Borovsky et al. (2012), Mani and Huettig (2012, 2014), and Mishra et al. (2012) is that skilled individuals may have a larger pool of working memory resources available to support prediction (e.g., for discussion, see Traxler, 2014). While no direct measure of working memory capacity (e.g., sentence span) was included in these studies, working memory capacity has been shown to correlate with the measures that these studies did investigate (e.g., Van Dyke, Johns, & Kukona, 2014). In addition, Huettig and Janse (2016) recently found that comprehenders with greater working memory capacity were more likely to launch predictive eye movements on the basis of gender-marked articles (e.g., Dutch "het" vs. "de"). Nevertheless, pervasive correlations among various cognitive measures, and the inclusion of only one or a handful of measures in prior studies, poses a challenge for understanding the determinants of comprehenders' prediction ability.

Thus far, we have highlighted research that focuses on one aspect of prediction: the *activation* of predictable outcomes. Recently, Kukona, Cho, Magnuson, and Tabor (2014) also addressed a related component, the *inhibition* of implausible outcomes. They demonstrated that local lexical (e.g., adjective) constraints interfered with prediction, drawing comprehenders' eye movements away from predictable outcomes. They found that undergraduate listeners hearing "The boy will eat the white …," while viewing a scene with a WHITE CAKE, BROWN CAKE, WHITE CAR, and BROWN CAR, fixated the WHITE CAKE (white, and edible) most. However, they also fixated the "competitor" WHITE CAR (white, but inedible) more than the distractor BROWN CAR. Similarly, Kukona, Fang, Aicher, Chen, and Magnuson (2011) found that undergraduate listeners hearing "Toby will arrest the…," while viewing a scene with a CROOK, POLICEMAN, unrelated distractors, and a recurring character named "Toby," fixated the CROOK (a good *patient* of arrest) most, but also fixated the "competitor" POLICEMAN (a good *agent* but not patient of arrest) more than distractors. These findings yield a critical insight into the mechanisms of prediction: while plausible outcomes are activated *most*, implausible outcomes that share features with the plausible target are also activated.

In this respect, prediction operates similarly to other cognitive operations that are governed by the principle of "global matching" (e.g., Clark & Gronlund, 1996), wherein partially matching representations are simultaneously activated, creating interference for identifying a correct target. Related interference effects have been observed at multiple linguistic levels, including phonological (e.g., rhyme effects; e.g., Allopenna, Magnuson, & Tanenhaus, 1998), lexical (e.g., lexical ambiguity resolution; Swinney, 1979; neighborhood effects; Mirman & Magnuson, 2009), syntactic (e.g., Bicknell, Levy, & Demberg, 2010; Konieczny, Müller, Hachmann, Schwarzkopf, & Wolfer, 2009; Konieczny, Weldle, Wolfer, Müller, & Baumann, 2010; Tabor, Galantucci, & Richardson, 2004; Van Dyke & Lewis, 2003) and semantic (e.g., Van Dyke, 2007; Van Dyke & McElree, 2006, 2011). Simultaneously, comprehenders' ability to inhibit partially matching representations has also been hypothesized to be crucial to skilled language comprehension (e.g., Gernsbacher & Faust, 1991).

Kukona et al. (2014) argue that the dynamic interplay between bottom-up activation of and inhibition among targets, feature-overlapping competitors, and unrelated distractors during anticipation can best be explained by positing a self-organizing cognitive architecture (e.g., Kukona & Tabor, 2011; Tabor & Hutchins, 2004). Building on language processing models such as the Interactive activation model of letter and word recognition (McClelland & Rumelhart, 1981) and TRACE (McClelland & Elman, 1986), they implemented a self-organizing artificial neural network that addressed the specific relationship between spoken language comprehension and eye movements in the visual world paradigm. Such an architecture assumes that (1) individual perceptual inputs activate lower-level representations that compete for dominance, and (2) competitive dynamics among these lower-level representations drive the activation of higher-level representations that best satisfy the combinatorial constraints of the input.

Thus, in the hypothesis of Kukona et al. (2014), mental representations of both the WHITE CAKE and WHITE CAR are activated by "white" in the speech stimulus, while WHITE CAKE competes with, and ultimately