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

Anuenue Kukona [a,*], David Braze [b], Clinton L. Johns [b], W. Einar Mencl [b], Julie A. Van Dyke [b], James S. Magnuson [b,c], Kenneth R. Pugh [b,c], Donald P. Shankweiler [b,c], Whitney Tabor [b,c]

[a] Division of Psychology, De Montfort University, Leicester, United Kingdom
[b] Haskins Laboratories, New Haven, CT, United States
[c] Department of Psychology, University of Connecticut, Storrs, CT, United States

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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

* Corresponding author at: Division of Psychology, De Montfort University, The Gateway, Leicester LE1 9BH, UK.
E-mail address: anuenue.baker-kukona@dmu.ac.uk (A. Kukona).

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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 dominates, WHITE CAR due to inhibition between the WHITE CAR and the more strongly activated WHITE CAKE. This architecture is "self-organizing" in that feedback interactions among the lower-level representations allow the system to ultimately reject the partially (mis)matching competitor and converge on a coherent response (i.e., *prediction*) to the input. Moreover, the architecture can be called self-organizing in that there is no overarching "controller." So, while representations that only partially match the input will become activated, structure will emerge because inhibition among the incompatible representations will cause the "best" representations to thrive and other representations to diminish. Thus, self-organization predicts that participants will activate the WHITE CAKE even before they have heard "cake" (i.e., due to support for the WHITE CAKE representation from both "eat" and "white"). However, it also predicts that participants will transiently activate competitors (e.g., WHITE CAR) that are supported by the input locally (e.g., the word "white") but not globally (e.g., the phrase "eat the white…"). The framework thus accounts for the dynamic interplay of excitatory and inhibitory processes on the activation of candidate representations and concomitant behaviors.

In summary, prediction has received considerable attention in recent psycholinguistic research. There are now many studies, using a variety of research techniques (eye movements over print, event-related potentials, the visual world paradigm), which strongly support the existence of predictive processes during language comprehension. Moreover, studies examining individual differences in comprehenders' predictive eye movements also point to a close link between prediction and language and literacy skill. A complete account of the language system must thus be able to explain variability in comprehenders' prediction ability. However, extant studies have left unresolved questions about the key (sub)skills that enable some comprehenders, but not others, to predict; rather, they have used largely non-overlapping sets of skill measures (e.g., receptive vocabulary: Borovsky et al., 2012; literacy: Mishra et al., 2012; pseudo-word reading: Mani & Huettig, 2014; productive vocabulary: Mani & Huettig, 2012), which make comparisons and generalizations difficult.

In the current study, we investigated individual differences in the predictive eye movements of a community-based sample of 16- to 24-year-old young adults, including many with low literacy skills. Most psychology and psycholinguistic studies are based on university students, which entails a restricted range of language and literacy skills toward the upper end of the distribution. By contrast, prior research has documented considerable variation in the language and literacy skills of comprehenders in the population from which the current sample is drawn (e.g., Braze, Tabor, Shankweiler, & Mencl, 2007; Braze et al., 2011, 2016; Kuperman & Van Dyke, 2011, 2013; Magnuson et al., 2011; Shankweiler et al., 2008; Van Dyke et al., 2014), especially in comparison to typical undergraduate samples. As in this previous work, our participants completed an extensive battery of measures that quantified their abilities along various dimensions, many of them implicated in comprehension processes (e.g., vocabulary, pseudo-word reading, etc.). In addition, they completed a visual world eye tracking study, which assessed their prediction ability in the context of a spoken sentence comprehension task. Motivated by our interest in self-organization (e.g., Kukona et al., 2014), we examined comprehenders' ability to both *activate* predictable outcomes and *inhibit* implausible outcomes. Our visual world task was based on Kukona et al. (2014): comprehenders heard sentences like "The boy will eat the white cake," while viewing visual arrays with objects like a WHITE CAKE, BROWN CAKE, WHITE CAR, and BROWN CAR (see Fig. 1). Comprehenders' eye movements to targets like WHITE CAKE before hearing the word "cake" were considered a measure of their prediction ability, and their eye movements to competitors like WHITE CAR provided a measure of their ability to inhibit implausible outcomes that shared features with predictable referents.

This design allowed us to assess potential determinants of comprehenders' prediction ability, to explore possible mechanisms supporting prediction, and to distinguish among a number of theoretical possibilities. For example, the capacity-based view (e.g., Just & Carpenter, 1992) predicts effects of working memory capacity on prediction: comprehenders with larger capacities should show more accurate or potentially faster predictive behaviors (e.g., as reflected in predictive eye movements to the WHITE CAKE) than comprehenders with smaller capacities. By contrast, the experience-based view of Mishra et al. (2012) predicts effects of reading experience on prediction: comprehenders with greater experience (and potentially, greater knowledge of statistics that are predictive of linguistic outcomes) should show enhanced predictive effects. This approach may also predict effects of speed of processing on prediction; Mishra et al. have suggested that limits on processing speed may limit comprehenders' ability to predict, such that less speedy individuals should show weaker effects. Alternatively, findings from prior research with other groups predict effects of vocabulary size (e.g., Borovsky et al., 2012; Mani & Huettig, 2012) and/or word reading (Mani & Huettig, 2014) on prediction: comprehenders with larger vocabularies and/or greater word reading skill should show enhanced predictive effects. Consistent with this prediction, Braze et al. (2007) found that vocabulary was a key determinant of literacy skills in the current population. With regard to the inhibition of competitors, the prior work of Gernsbacher and colleagues (e.g., Gernsbacher & Faust, 1991), who have shown that less skilled comprehenders are less able to suppress irrelevant, inappropriate, and interfering information, predicts that less skilled comprehenders should show larger interference effects (e.g., as reflected in eye movements to the WHITE CAR). Finally, our extensive battery allowed us to evaluate potentially spurious relations between skill and prediction, which could stem from shared variance among skill measures.

2. Experiment

We investigated the relationship between comprehenders' predictive behaviors and their language and literacy skills. Participants completed both a visual world eye tracking study (e.g., hearing sentences such as "The boy will eat the white…," while viewing a scene with a WHITE CAKE, BROWN CAKE, WHITE CAR, and BROWN CAR) and an extensive battery of skill measures.

2.1. Method

2.1.1. Participants

77 English native speakers participated for $15 per hour.[1] Participants were recruited via presentations, ads, posters, and/or flyers in community colleges and other public locations. All participants scored at 70% or above on the Fast Reading subtest of the Stanford Diagnostic Reading Test, fourth edition (Karlson & Gardner, 1995), and none had a diagnosed reading or learning disability. The performance of individuals in this sample on reading ability tasks was well below the levels typically seen in university students (e.g., see the grade-equivalent scores in Table 1). We excluded a total of 7 participants ($N = 70$): 5 participants with an IQ of 70 or below and 2 participants with missing data.

2.1.2. Materials

Our visual world materials were based directly on Kukona et al. (2014). Each of our 16 unique sentences (e.g., "The boy will eat the white/brown cake;" for the full set of sentences, see Appendix 1 of Kukona et al., 2014) was associated with a verb-predicted target (e.g., cake), a non-verb-predicted competitor (e.g., car), two color adjectives (e.g., white/brown), and a visual display with four clip-art objects, which reflected the crossing of the target and competitor objects with the color adjectives (see Fig. 1). The experiment used a 2 × 2 design,

[1] Participants in the current study were a subset of those who participated in Braze et al. (2016).

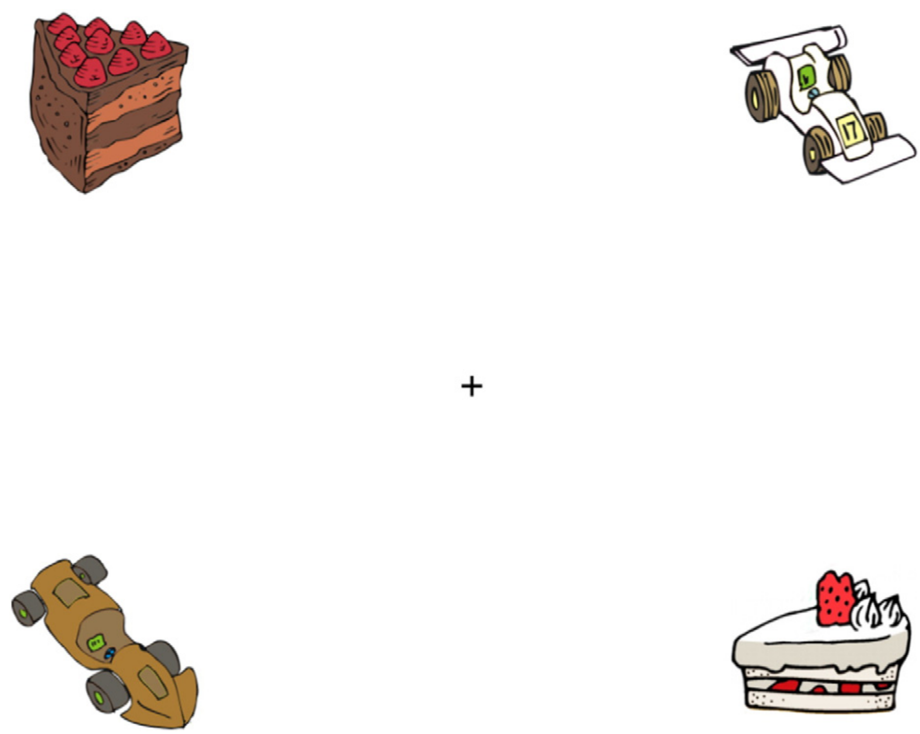

Fig. 1. Example visual display from the visual world experiment. Participants heard the example sentence "The boy will eat the white cake."

with factors of verb consistency (consistent and inconsistent) and adjective consistency (consistent and inconsistent). For the example sentence "The boy will eat the white cake," the visual display included a verb-consistent and adjective-consistent white cake, a verb-consistent and adjective-inconsistent brown cake, a verb-inconsistent and adjective-consistent white car, and a verb-inconsistent and adjective-inconsistent brown car. Thus, participants always heard predictable sentences, and all four conditions were represented in each visual display. Half of participants heard one of the adjectives (e.g., "white"), while the other half heard the other adjective (e.g., "brown"). Participants heard each of the 16 unique sentences frames once across the experiment. Adjectives, object locations, and sentence orders were randomized for each participant. The visual world study was completed after the skill measures.

2.1.3. Procedure

We used an SR Research EyeLink II head-mounted eye tracker, sampling at 500 Hz. Participants were instructed to use the computer mouse to click on the object described in each sentence. Participants began trials by clicking on a central fixation cross. The onset of the visual stimulus preceded the onset of the spoken stimulus by 500 ms. Trials ended when participants clicked on an object. The experiment began with four practice trials with feedback, and was approximately 15 min in length.

2.1.4. Individual difference measures

Our battery included over two-dozen measures, which assessed a range of language and cognitive skills. The battery was composed of standardized assessments that have been widely used in clinical and educational settings, and/or the psycholinguistics literature. Each of the measures is described briefly below, and further details (e.g., administration, validity, reliability, etc.) are provided in Braze et al. (2007, 2011, 2016), Kuperman and Van Dyke (2011, 2013), Magnuson et al. (2011), and Van Dyke et al. (2014).

The battery focused on several key skills: reading and listening comprehension, vocabulary, decoding, reading fluency, rapid automatized naming (RAN), phonological skills, and print experience, with several measures of each. Reading comprehension was assessed via the Gates-MacGinitie Reading Tests, fourth edition (GM; MacGinitie, MacGinitie, Maria, & Dreyer, 2000), odd numbered items of the Peabody Individual Achievement Test-Revised (PIAT; Markwardt, 1998), the passage comprehension subtest of the Woodcock-Johnson-III Tests of Achievement (WJ; Woodcock, McGrew, & Mather, 2001), and the fast reading subtest of the Stanford Diagnostic Reading Test, fourth edition (SDRT; Karlson & Gardner, 1995). Listening comprehension was assessed via even numbered items of the PIAT and the oral comprehension subtest of the WJ. Vocabulary was assessed via the Peabody Picture Vocabulary Test-Revised (Dunn & Dunn, 1997) and the vocabulary subtest of the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999). Decoding words (W) was assessed via the sight word efficiency subtest of the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999) and the letter-word identification subtest of the WJ, and decoding nonwords (NW) was assessed via the phonemic decoding efficiency subtest of TOWRE and the word attack subtest of the WJ.

In addition, oral reading fluency was assessed via three passages from the Gray Oral Reading Test, fourth edition (Wiederholt & Bryant, 2001) and silent reading fluency with the relevant subtest of the WJ. RAN was assessed via the rapid color, digit, and letter naming subtests of the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999). Finally, phonological skills were assessed via tests of phonological awareness (CTOPP: elision and blending words) and phonological memory (CTOPP: memory for digits and non-word repetition), and print experience was assessed via recognition of authors and magazines (based on Cunningham & Stanovich, 1990).

Additional measures assessed the following general cognitive capacities: working memory (based on Daneman & Carpenter, 1980), visuospatial memory (Corsi Blocks; Berch, Krikorian, & Huha, 1998; Corkin, 1974), and matrix reasoning (WASI; Wechsler, 1999). Finally, our battery also included the anti-saccade task (Hallett, 1978), in which participants made eye movements either towards (Saccade accuracy) or away (Anti-saccade accuracy) peripheral targets.

Table 1
Means, standard deviations, ranges, and maximum possible scores for the individual difference measures. Grade-equivalent scores are also reported for the PIAT and WJ measures.

Measure	M	SD	Range	Max
1. Reading GM	28.93	9.14	8–46	48
2. Reading PIAT	26.46	7.24	7–41	41
Grade	6.43	2.86	2–13	–
3. Reading SDRT	13.47	6.88	1–30	30
4. Reading WJ	33.40	3.62	26–42	47
Grade	7.89	3.97	3.10–19	–
5. Listening PIAT	27.51	7.05	11–40	41
Grade	6.84	2.76	2.30–13	–
6. Listening WJ	22.81	4.16	9–32	34
Grade	10.57	5.57	2–18	–
7. Vocab PPVT	153.20	20.62	107–191	204
8. Vocab WASI	40.04	9.25	21–64	66
9. Decoding W TOWRE	86.63	11.62	57–104	104
10. Decoding W WJ	61.80	5.68	49–75	76
Grade	8.80	3.51	4–19	–
11. Decoding NW TOWRE	39.70	14.20	7–63	63
12. Decoding NW WJ	24.00	5.22	13–32	32
Grade	8.00	4.59	2.50–19	–
13. Fluency GORT	19.43	6.90	2–30	30
14. Fluency WJ	64.47	14.08	42–98	98
Grade	10.06	3.98	4.70–19	–
15. RAN colors	40.30	9.33	28–88	–
16. RAN digits	23.22	4.39	15–37	–
17. RAN letters	25.47	5.34	17–46	–
18. Phonological awareness	81.47	15.63	55–115	150
19. Phonological memory	94.13	11.66	64–118	150
20. Print authors	2.07	2.82	−6–10	80
21. Print magazines	4.90	4.31	−2–14	80
22. Working memory	37.77	9.57	8–55	60
23. Visuospatial memory	4.92	1.00	3.10–7.20	9
24. Matrix reasoning	25.77	3.74	18–34	35
25. Saccade accuracy	0.96	0.04	0.78–1.00	1.00
26. Anti-sacc accuracy	0.85	0.12	0.48–1.00	1.00
27. IQ	88.30	11.18	72–123	–
28. Age	19.68	2.43	16.34–24.83	–
29. Years of education	11.23	0.92	9–13	–

Note. N = 70. GM = Gates-MacGinitie Reading Tests, fourth edition (MacGinitie et al., 2000); GORT = Gray Oral Reading Test, fourth edition (Wiederholt & Bryant, 2001); SDRT = Stanford Diagnostic Reading Test, fourth edition (Karlson & Gardner, 1995); TOWRE = Test of Word Reading Efficiency (Torgesen et al., 1999); PIAT = Peabody Individual Achievement Test-Revised (Markwardt, 1998); WJ = Woodcock-Johnson-III Tests of Achievement (Woodcock et al., 2001); and WASI = Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999). W = word; NW = nonword.

2.2. Results

2.2.1. Descriptive summary of individual difference measures

Means, standard deviations, and ranges for each measure are reported in Table 1. We also include descriptive summaries of full-scale IQ (computed from the WASI vocabulary and matrix reasoning subtests), age, and years of education, and grade-equivalent scores for the PIAT and Woodcock-Johnson-III measures. Simple correlations among the measures are reported in Table 2. For all measures except the RAN measures, higher scores reflect better performance and lower scores worse performance.

2.2.2. Composite measures

Our test battery included multiple measures of several key skills, which we used to generate composites scores. These are: *comprehension* (measures 1–8 in Tables 1 and 2), *decoding and fluency* (9–14), *RAN* (15–17), *phonological skills* (18–19), and *print experience* (20–21). Our composites were generated based on both theoretical and empirical considerations. Generally, the sets of measures that were included within each composite were designed to assess similar theoretical constructs, typically via similar tasks. Additionally, the results of Braze et al. (2016) are especially relevant: CFA/SEM was used to address factor structure in a subset of individual difference measures on a superset of individuals (N = 283), both relative to the current study. Two important conclusions emerged from their analysis. First, the vocabulary measures at hand were not distinct from the listening comprehension measures (also see Protopapas, Simos, Sideridis, & Mouzaki, 2012; Tunmer & Chapman, 2012). Second, the listening and reading comprehension factors also showed poor discriminant validity, supporting our decision to collapse them into a single construct in the current study. Alternatively, other work indicates that while measures of decoding skill and oral reading fluency show some evidence of separation, their discriminant capacity is rather low (Protopapas, Sideridis, Mouzaki, & Simos, 2007; Schwanenflugel et al., 2006; Tilstra, McMaster, Van den Broek, Kendeou, & Rapp, 2009). In the current study, our decoding and fluency measures also similarly required participants to read words, nonwords, and/or sentences accurately and fluently, and they showed considerable shared variance, supporting our decision to collapse them into a single construct. Finally, we also carried out an exploratory factor analysis on the current set of measures. It too revealed a pattern of association among measures that closely reflects the alignment of measures to constructs that we have adopted here (see Appendix A).

We generated composites by averaging standardized scores on each measure; composites were then re-standardized before subsequent analysis. For all composites including the RAN composite, higher scores reflect better performance and lower scores worse performance (i.e., the RAN measures were first transformed by subtracting participants' scores from the maximum observed score). Table 3 shows correlations among the composites (1–5) and additional simple measures (6–10) that are used in our eye movement analyses.

2.2.3. Eye movement analyses

Mean (*SE*) proportions of fixations to each object are plotted from the onset of the verb in Fig. 2. Eye movements were synchronized to the onset of each word (these varied across trials due to differences in word durations for different items; thus, the zero time points show data at the word onsets across all trials). We use the labels WHITE CAKE, BROWN CAKE, WHITE CAR and BROWN CAR, and the example sentence "The boy will eat the white cake," to distinguish the objects, although all 16 trials presented to participants were included in our analyses. In order to address the activation of predicted targets (e.g., WHITE CAKE), we compared eye movements to verb-consistent objects (e.g., cakes). Our analysis window spanned the onset of "the" to the onset of "cake" (i.e., immediately preceding the direct object noun), and excluded eye movements launched prior to the onset of "the," encompassing the period when we expected predictive effects to emerge. For each participant, we computed difference scores[2] by subtracting the mean proportions fixations to the adjective-inconsistent BROWN CAKE from the adjective-consistent WHITE CAKE across the window, aggregated over all items. Positive difference scores (*maximum possible* = 1.00) indicate more fixations to the WHITE CAKE, negative difference scores (*minimum possible* = −1.00) indicate more fixations to the BROWN CAKE, and scores of zero indicate no difference between the WHITE CAKE and BROWN CAKE. The mean difference score for WHITE CAKE vs. BROWN CAKE was 0.06 (*range* = −0.14–0.24; *SD* = 0.09).

In order to address the inhibition of implausible competitors (e.g., WHITE CAR), we also compared eye movements to the verb-inconsistent objects (e.g., cars). However, up to the onset of "cake" (and even through the offset of the sentence), the average proportions of fixations to the WHITE CAR and BROWN CAR differed to a much smaller degree than to the WHITE CAKE and BROWN CAKE (compare the purple vs. green curves to

[2] The current analyses differed from Kukona et al. (2014) in two critical respects. First, the use of difference scores allowed us to remove consistency (i.e., as a predictor) from our models, thus simplifying the interpretation of the individual differences effects (nevertheless, our models also tested for "main" effects of consistency as the intercept term, and revealed a similar pattern to Kukona et al., 2014). Second, the analysis windows spanned a larger time period, thus maximizing potential between-participants variability (i.e., individual differences).

Table 2
Correlations among the individual difference measures.

Measure	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.	21.	22.	23.	24.	25.
1. Reading GM																									
2. Reading PIAT	0.62																								
3. Reading SDRT	0.71	0.59																							
4. Reading WJ	0.75	0.61	0.73																						
5. Listening PIAT	0.57	0.75	0.52	0.60																					
6. Listening WJ	0.71	0.66	0.69	0.72	0.62																				
7. Vocab PPVT	0.71	0.81	0.77	0.76	0.77	0.76																			
8. Vocab WASI	0.67	0.62	0.71	0.74	0.68	0.70	0.76																		
9. Decoding W TOWRE	0.65	0.47	0.60	0.61	0.39	0.42	0.57	0.57																	
10. Decoding W WJ	0.71	0.66	0.71	0.74	0.52	0.55	0.73	0.70	0.79																
11. Decoding NW TOWRE	0.59	0.42	0.52	0.58	0.32	0.47	0.48	0.47	0.78	0.74															
12. Decoding NW WJ	0.50	0.46	0.44	0.55	0.37	0.36	0.45	0.42	0.68	0.70	0.83														
13. Fluency GORT	0.67	0.60	0.66	0.65	0.45	0.47	0.65	0.55	0.76	0.82	0.74	0.68													
14. Fluency WJ	0.66	0.47	0.84	0.64	0.50	0.60	0.62	0.64	0.67	0.67	0.61	0.51	0.67												
15. RAN colors	−0.23	−0.14	−0.12	−0.10	−0.05	−0.19	−0.05	−0.11	−0.38	−0.16	−0.32	−0.24	−0.20	−0.23											
16. RAN digits	−0.48	−0.33	−0.42	−0.43	−0.21	−0.33	−0.34	−0.30	−0.70	−0.52	−0.64	−0.52	−0.51	−0.44	0.53										
17. RAN letters	−0.39	−0.23	−0.32	−0.35	−0.11	−0.30	−0.23	−0.23	−0.57	−0.43	−0.55	−0.45	−0.46	−0.40	0.59	0.83									
18. Phonological awareness	0.61	0.57	0.51	0.59	0.55	0.52	0.63	0.63	0.50	0.60	0.57	0.54	0.47	0.48	−0.13	−0.37	−0.26								
19. Phonological memory	0.41	0.47	0.38	0.43	0.36	0.32	0.38	0.37	0.34	0.39	0.32	0.37	0.35	0.29	0.00	−0.31	−0.14	0.39							
20. Print authors	0.48	0.42	0.72	0.55	0.37	0.46	0.59	0.54	0.51	0.56	0.40	0.32	0.54	0.60	0.03	−0.43	−0.27	0.37	0.19						
21. Print magazines	0.17	0.23	0.35	0.30	0.36	0.36	0.37	0.36	0.23	0.27	0.25	0.20	0.28	0.38	0.11	0.00	0.06	0.12	0.01	0.51					
22. Working memory	0.56	0.38	0.42	0.48	0.40	0.41	0.47	0.50	0.50	0.51	0.44	0.47	0.43	0.42	−0.07	−0.28	−0.21	0.54	0.34	0.38	0.18				
23. Visuospatial memory	0.34	0.36	0.29	0.26	0.27	0.17	0.22	0.13	0.31	0.37	0.46	0.39	0.42	0.25	−0.24	−0.33	−0.21	0.32	0.46	0.11	−0.05	0.18			
24. Matrix reasoning	0.61	0.64	0.41	0.62	0.60	0.50	0.59	0.50	0.35	0.49	0.43	0.42	0.37	0.35	−0.17	−0.34	−0.29	0.65	0.41	0.29	0.16	0.46	0.32		
25. Saccade accuracy	0.21	0.16	0.07	0.13	0.18	0.10	0.15	0.03	0.14	0.21	0.34	0.30	0.26	0.14	−0.16	−0.25	−0.20	0.15	0.07	−0.06	0.07	0.10	0.24	0.25	
26. Anti-sacc accuracy	0.31	0.18	0.08	0.12	0.11	0.21	0.14	0.18	0.25	0.24	0.21	0.12	0.12	0.12	−0.31	−0.31	−0.24	0.23	0.17	−0.01	−0.09	0.10	0.16	0.26	0.16

Note. $|r| \geq .24$, $p < .05$; $|r| \geq .31$, $p < .01$; $|r| \geq .39$, $p < .001$.

Table 3
Correlations among the composite measures.

Measure	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Comprehension									
2. Decoding & fluency	0.75								
3. RAN	0.33	0.56							
4. Phonological skills	0.68	0.60	0.28						
5. Print experience	0.56	0.50	0.11	0.24					
6. Working memory	0.53	0.53	0.21	0.53	0.32				
7. Visuospatial memory	0.30	0.42	0.30	0.47	0.04	0.18			
8. Matrix reasoning	0.65	0.46	0.30	0.64	0.26	0.46	0.32		
9. Saccade accuracy	0.15	0.27	0.23	0.13	0.00	0.10	0.24	0.25	
10. Anti-sacc accuracy	0.19	0.20	0.33	0.24	−0.06	0.10	0.16	0.26	0.16

Note. $|r| \geq .24$, $p < .05$; $|r| \geq .31$, $p < .01$; $|r| \geq .39$, $p < .001$.

the red vs. blue curves in Fig. 2). In order to better capture the pattern among competitors, and to allow for greater individual differences in fixations to the WHITE CAR and BROWN CAR (preliminary analyses revealed that this difference was reliable but much smaller prior to the onset of "cake" compared to after it), we used a later analysis window for competitors. This competitor analysis window spanned the onset to the offset of "cake," and excluded eye movements launched prior to the onset of "cake." For each participant, we computed difference scores by subtracting the mean proportions of fixations to the adjective-inconsistent BROWN CAR from the adjective-consistent WHITE CAR across the window, aggregated over all items. Positive difference scores indicate more fixations to the WHITE CAR, negative difference scores indicate more fixations to the BROWN CAR, and scores of zero indicate no difference between the WHITE CAR and BROWN CAR. The mean difference score for WHITE CAR vs. BROWN CAR was 0.05 (range $= -0.07$–0.21; $SD = 0.05$)

We submitted difference scores in both the CAKE conditions and the CAR conditions to two sets of linear regression analyses ("lm" in *R*). In the first set of simple linear regression analyses ("Single predictor models"), we submitted difference scores to separate models for each of the 10 individual difference measures under consideration (see Table 3). (For completeness, we also report parallel Single predictor models for all the individual difference measures [see Tables 1 and 2], and not just the composites, in Appendix B.) Primarily, this first set of analyses allowed us to compare the current results to prior studies examining closely related skills in isolation of the other measures in our battery. Models included only one individual difference measure as a predictor. In the second set of linear regression analyses ("Multiple predictor models"), we submitted difference scores to models that simultaneously included all of the 10 individual difference measures under consideration (see Table 3). The second set of analyses allowed us to

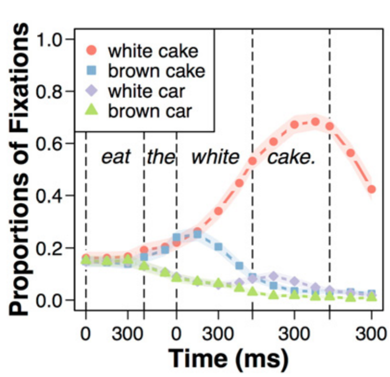

Fig. 2. Mean proportions of fixations (shaded bands show *SE*) to the verb-consistent and adjective-consistent WHITE CAKE, verb-consistent and adjective-inconsistent BROWN CAKE, verb-inconsistent and adjective-consistent WHITE CAR, and verb-inconsistent and adjective-inconsistent BROWN CAR conditions during the example sentence "The boy will eat the white cake." Fixations were resynchronized at the onset of each word, and extend to their mean offset.

address whether particular skills were unique predictors of our eye movement patterns. These models included all of the individual difference measures as predictors. All continuous measures were converted to standard scores ($M = 0$, $SD = 1$), and we report βs for each term. Finally, the intercept term in our models assessed whether there was a reliable difference between WHITE CAKE vs. BROWN CAKE or WHITE CAR vs. BROWN CAR for an "average" comprehender (i.e., with a standardized score of zero on each measure).

2.2.4. Single predictor models

The analyses of difference scores in the verb-consistent cake conditions revealed a reliable intercept across all models (all $ts > 5.13$, all $ps < .001$), revealing reliably more eye movements to the WHITE CAKE than BROWN CAKE for individuals with average scores on each skill measure. Similarly, the analyses of difference scores in the verb-inconsistent car conditions revealed a reliable intercept across all models (all $ts > 7.91$, all $ps < .001$), revealing reliably more eye movements to the WHITE CAR than BROWN CAR for an "average" comprehender. Effects of each of our individual difference measures are reported in Table 4. To illustrate the pattern of results, regression fits are plotted in Fig. 3. Analyses of eye movements to the verb-consistent cakes revealed reliable effects of four measures (Comprehension, Decoding & fluency, RAN, and Matrix Reasoning), such that more skilled individuals (with higher scores) showed a larger WHITE CAKE vs. BROWN CAKE advantage than less skilled individuals (with lower scores) on these measures. Analyses of eye movements to the verb-inconsistent cars revealed reliable effects of one individual difference measure (Comprehension), such that less-skilled individuals showed a larger WHITE CAR vs. BROWN CAR advantage than more skilled individuals. These single predictor models provide us a point of comparison with prior research (for parallel analyses of all the individual difference measures, and not just the composites, see Appendix B.). However, only RAN (in predicting the WHITE CAKE vs. BROWN CAKE advantage) survives a Bonferroni correction for multiple comparisons ($p < .05/10$ measures $= .005$), converging with our multiple predictor models.

2.2.5. Multiple predictor models

We also addressed whether particular skills uniquely predicted our eye movement patterns. Multiple predictor models are reported in Table 5. Examination of kappa (<10) and the variance inflation factor (<5) indicated that multicollinearity was not a problem in our models. The analyses of difference scores in the verb-consistent cake conditions revealed a reliable effect of RAN, such that more skilled individuals (with higher scores) showed a larger WHITE CAKE vs. BROWN CAKE advantage than less skilled individuals (with lower scores) on this measure (i.e., closely resembling its corresponding single predictor model). The analyses of difference scores in the verb-inconsistent car conditions revealed a reliable effect of comprehension and RAN, such that better

Table 4
Regression results for the single predictor simple linear regression analyses with the composite measures. Each β reflects a separate regression model.

	White vs. brown cake				*White vs. brown car*			
	β[a]	*SE*[a]	*t*	*p*	β[a]	*SE*[a]	*t*	*p*
1. Comprehension	2.51	1.07	2.35	<.05	−1.39	0.59	−2.37	<.05
2. Decoding & fluency	2.79	1.06	2.64	<.05	−0.44	0.61	−0.73	.47
3. RAN	3.69	1.02	3.62	<.001	0.82	0.60	1.36	.18
4. Phonological skills	2.10	1.08	1.94	.06	−0.65	0.61	−1.08	.28
5. Print experience	1.13	1.10	1.02	.31	−0.42	0.61	−0.70	.49
6. Working memory	1.46	1.10	1.33	.19	−0.47	0.61	−0.78	.44
7. Visuospatial memory	2.14	1.08	1.97	.05	0.32	0.61	0.53	.60
8. Matrix reasoning	2.48	1.07	2.31	<.05	−0.85	0.60	−1.41	.16
9. Saccade accuracy	1.62	1.09	1.48	.14	−0.16	0.61	−0.27	.79
10. Anti-sacc accuracy	1.87	1.09	1.72	.09	−0.37	0.61	−0.61	.54

[a] β and *SE* values $\times 10^{-2}$.

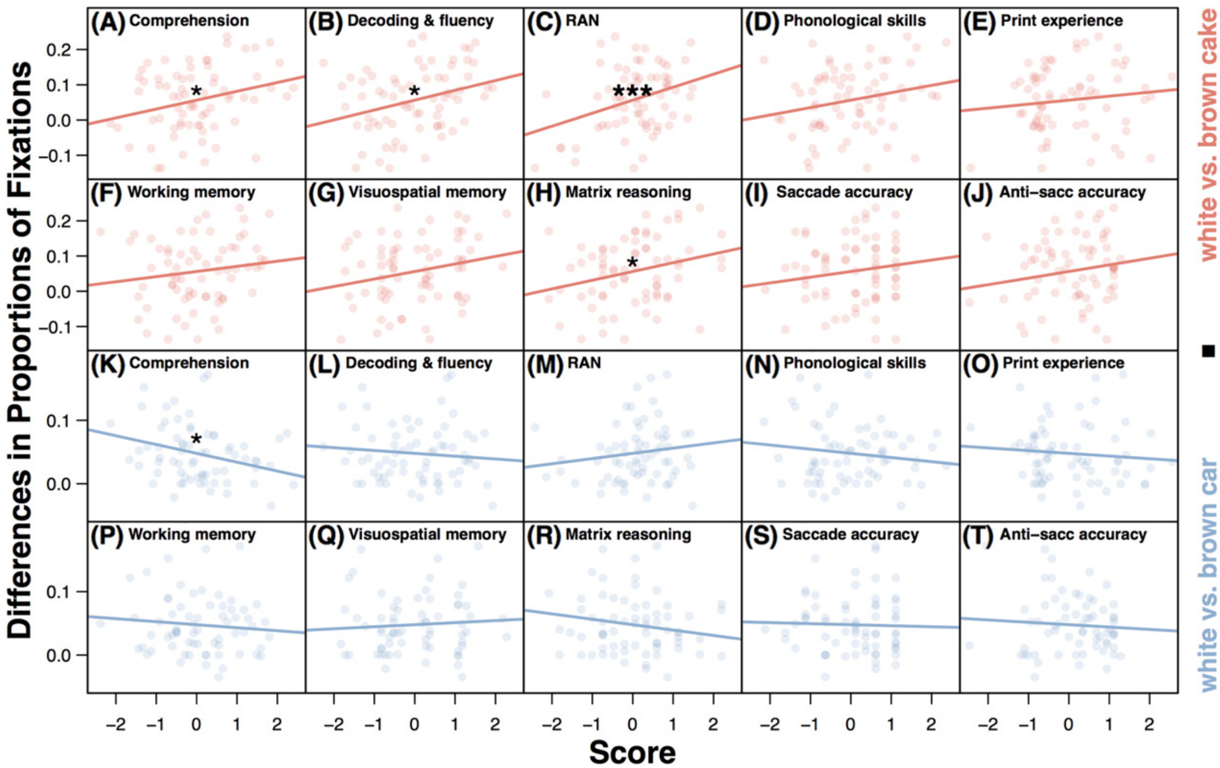

Fig. 3. Scatterplots showing the relationship between each composite measure (x-axis) and differences in proportions of fixations (y-axis) to the verb-consistent WHITE CAKE *minus* BROWN CAKE (A–J) and verb-inconsistent WHITE CAR *minus* BROWN CAR (K–T). Lines represent regression fits from the single predictor models (*$p < .05$; **$p < .01$; ***$p < .001$).

comprehenders showed a smaller WHITE CAR vs. BROWN CAR advantage than poor comprehenders (i.e., closely resembling its corresponding single predictor model), while conversely individuals with better RAN performance showed a larger WHITE CAR vs. BROWN CAR advantage than those with lower RAN scores.

3. General discussion

3.1. Activation of predictable outcomes

In the current study, we investigated relations between comprehenders' prediction ability and their language and literacy skills. Our results are compatible with prior research in two critical ways: first, we observed clear predictive effects, such that comprehenders *on average* generated expectations about future linguistic input and outcomes, and launched predictive eye movements on the basis of these expectations; and second, we observed systematic variation across individuals in the magnitude of these effects. While skilled individuals (i.e., as broadly reflected in their comprehension, decoding & fluency, RAN, and matrix reasoning skills) hearing "The boy will eat the white…" generated expectations about, and launched eye movements to, the WHITE CAKE (much like the undergraduate sample from Kukona et al., 2014), less skilled comprehenders showed much weaker effects. Our results extend the pattern previously observed in university undergraduates to a community-based sample of young adults who fall along a broad swath of the language and literacy skills continuum (vs. college students who represent a more restricted range of skill; e.g., see the grade-equivalent scores in Table 1).

Our (white vs. brown cake) single predictor models revealed a number of specific individual difference patterns that are consistent with prior findings. We observed a positive relationship between prediction ability and both the comprehension composite (see Fig. 3A), which included vocabulary skill as a component (see Borovsky et al., 2012; Mani & Huettig, 2012), and the decoding & fluency composite (see Fig. 3B), which included word reading as component (see Mani & Huettig, 2014). Finally, we also observed effects of RAN (see Fig. 3C) and matrix reasoning (see Fig. 3H), and marginal effects of phonological skills (see Fig. 3D), visuospatial memory (see Fig. 3G), and anti-sacc accuracy (see Fig. 3J). These results from our single predictor models suggest a link between prediction and language and literacy skill. At the same time, our various skill measures were highly intercorrelated, indicating a considerable degree of shared variance (see Tables 2 and 3). Consequently, some of our effects – and similarly related effects in prior research – could reflect spurious relations between some skill measures and prediction-related behaviors. For example, Matrix reasoning was reliably correlated with *every* other composite measure, suggesting that its relation to prediction-related eye movement behaviors could be a merely incidental function of these various associations. Our multiple predictor model allowed us to address this issue and gain new insight into the more plausible determinants of comprehenders' prediction ability. That model revealed that only RAN uniquely accounted for individual

Table 5
Regression results for the multiple predictor linear regression analyses with the composite measures. The βs for white vs. brown cake reflect one regression model, and the βs for white vs. brown car reflect a second regression model.

	White vs. brown cake				*White vs. brown car*			
	β[a]	*SE*[a]	*t*	*p*	β[a]	*SE*[a]	*t*	*p*
(Intercept)	5.62	1.06	5.32	<.001	4.79	0.59	8.18	<.001
Comprehension	0.99	2.15	0.46	.65	−2.54	1.19	−2.13	<.05
Decoding & fluency	−0.72	2.15	−0.33	.74	−0.25	1.19	−0.21	0.83
RAN	2.99	1.40	2.13	<.05	1.63	0.78	2.09	<.05
Phonological skills	−0.10	1.77	−0.06	.96	0.43	0.98	0.44	.66
Print experience	0.45	1.41	0.32	.75	0.76	0.78	0.98	.33
Working memory	0.02	1.36	0.02	.99	0.21	0.76	0.28	.78
Visuospatial memory	0.85	1.29	0.66	.51	0.59	0.72	0.83	.41
Matrix reasoning	0.66	1.60	0.41	.68	−0.16	0.89	−0.18	.86
Saccade accuracy	0.55	1.16	0.47	.64	−0.19	0.64	−0.3	.77
Anti-sacc accuracy	0.51	1.17	0.43	.67	−0.46	0.65	−0.72	.48

[a] β and *SE* values $\times 10^{-2}$.

variation in prediction ability, as reflected in the activation of the predictable target (correcting for multiple comparisons among the single predictor models revealed a similar pattern, with only RAN falling below the threshold).

The current study is the first to investigate the relation between rapid automatized naming and prediction, and to reveal that rapid naming (i.e., the RAN composite) is a key determinant of comprehenders' prediction ability. Our results reveal that individuals who perform better on RAN are better able to launch predictive eye movements on the basis of their expectations about future linguistic input. In the standardized rapid naming tasks used in our study, participants were presented with a 4×9 grid of items (digits, letters, or colored squares for each task), and they were instructed to say the name of each item as quickly as possible in a left-to-right, top-to-bottom serial order (Wagner et al., 1999). Research on reading development has shown that rapid naming is among a small number of "measures that most consistently predict future reading difficulty in English" (Norton & Wolf, 2012, p. 439). For example, Scarborough (1998) found that rapid object naming performance in Grade 2 predicted reading skills in Grade 8.

Currently, there is a lack of consensus regarding what RAN is a measure of. One possibility is that rapid naming taps into comprehenders' generalized speed of processing (e.g., Catts, Gillispie, Leonard, Kail, & Miller, 2002; Kail & Hall, 1994). Catts et al. (2002) showed that response times in motor, visual, lexical, grammatical, and phonological tasks (i.e., aimed at assessing domain general speed of processing) patterned with rapid object naming in explaining reading achievement in children. Thus, one interpretation of the current findings is that comprehenders' generalized speed of processing provides considerable constraint on their prediction ability. Undoubtedly, speed is crucial to prediction: not only does prediction require comprehenders to generate expectations about future input and outcomes, but it also requires them to do so in a timely fashion (i.e., *before* the input/outcomes of interest are revealed). Given the rapid pace with which spoken language unfolds, our findings thus suggest that deficits in comprehenders' generalized speed of processing may limit their ability to generate expectations in a timely fashion may (e.g., within the few hundred millisecond lifetime of an unfolding word like "white;" see also Huettig & Janse, 2016; Mishra et al., 2012). In contrast, Norton and Wolf (2012) have argued that rapid naming taps into "a microcosm of the processes involved in reading" (p. 427), including comprehenders' "ability to automate both the individual linguistic and perceptual components and the connections among them in visually presented serial tasks" (p. 430). Thus, another interpretation of the current findings is that comprehenders' ability to automate linguistic processes may constrain their prediction ability. Nevertheless, this perspective also likely entails closely related constraints on comprehenders' speed of processing.

In the current study, we used sentence materials that are quite typical of visual world prediction studies (e.g., involving constraints from a verb and another linguistic element; e.g., Borovsky et al., 2012; Kamide, Altmann, & Haywood, 2003; Kukona et al., 2011). As in prior studies, our materials involved a simple and frequent (e.g., subject-verb-object) construction. Consequently, the current individual difference results may be specific to simple and frequent linguistic inputs. Nevertheless, we did not find evidence that comprehenders were at ceiling performance with these materials (e.g., such that all participants uniformly predicted the target, eliminating our ability to detect individual differences); rather, our results suggest that there was considerable individual variation in eye movements (e.g., difference scores ranged between −0.14 and 0.24 for WHITE CAKE vs. BROWN CAKE, out of a possible range of −1.00 to 1.00). At the same time, the current materials were more complex than those used in many prior individual differences studies; for example, while prediction in the current study depended on two linguistic elements (i.e., verb plus adjective), in Mani and Huettig (2012, 2014), Mishra et al. (2012), and Huettig and Janse (2016), predictions could be made on the basis of a single element (e.g., a verb or gender-marked particle, adjective or article). In this regard, the current study allows us to assess individual differences in sentence-level prediction based on multiple linguistic elements (see also Borovsky et al., 2012).

Finally, our results also bear on a number of other theoretical predictions. The current study also investigated the potential relation of working memory capacity to prediction, measured using the sentence span task (e.g., Daneman & Carpenter, 1980) that is pervasive in the sentence processing literature. Our results suggest that working memory capacity is not a reliable predictor of prediction ability. Thus, these results provide no evidence in support of a capacity-based account of prediction (e.g., Just & Carpenter, 1992), or for the claim that working memory capacity is an important limiting factor in language comprehension (see also Van Dyke et al., 2014 for a similar finding). By contrast, while Borovsky et al. (2012) and Mani and Huettig (2012) found that (e.g., 3- to 10-year-old and 2-year-old) comprehenders' vocabularies were more robust predictors, the comprehension composite was not reliable in our (white vs. brown cake) multiple predictor model. This discrepancy may stem from differences in our participants, or developmental changes in the relationship. Alternatively, the apparent instability of this correlation (note that prediction ability was also unrelated to receptive vocabulary in 2-year-olds; Mani & Huettig, 2012) suggests that it may depend on its shared variance with another variable, like rapid naming (which was not assessed in prior studies). On the other hand, we did find an effect of the comprehension composite on the inhibition of implausible competitors; this may suggest a more nuanced relationship between vocabulary and prediction, which we discuss below. Finally, while a reliable relation between word reading skill and prediction ability was observed both here (i.e., as reflected in the decoding & fluency composite) and in Mani and Huettig (2014), the results of our multiple predictor model suggests that this may also depend on its shared variance with another variable, like rapid naming.

In summary, these data support the idea that speedier processing of lower-level linguistic detail (potentially via the automation of these processes; e.g., Norton & Wolf, 2012) promotes prediction of higher-level (e.g., combinatorial/sentential) outcomes by allowing for speedier computations (e.g., of predictions/expectations), such that speed of processing serves as a key determinant of comprehenders' prediction ability (see also Perfetti & Hart, 2002). Moreover, by examining a range of skills, these data highlight the key contribution of speed, rather than knowledge *per se* (e.g., Borovsky et al., 2012; Mani & Huettig, 2012; Mani & Huettig, 2014), in anticipation. However, by no means do our data rule out a role for knowledge in anticipation; in fact, our results also reveal a close connection between comprehension skill and the inhibition of implausible competitors, which we turn to next.

3.2. Inhibition of implausible competitors

In addition to examining individual differences in comprehenders' ability to *activate* predictable outcomes, we also examined their ability to *inhibit* implausible outcomes that share some features with predictable referents. Consistent with Kukona et al. (2014), we observed clear interference effects from competitor objects in the visual display: on average, comprehenders hearing "The boy will eat the white…" fixated the improbable competitor (e.g., white but inedible) WHITE CAR more than the distractor BROWN CAR. This study is the first to reveal skill-based individual differences in these effects: our multiple predictor model revealed that both the comprehension and RAN composites accounted for unique variance in comprehenders' ability to inhibit the WHITE CAR. On the one hand, skilled comprehenders (see Fig. 3K) showed less interference (e.g., a smaller WHITE CAR vs. BROWN CAR advantage) than their less skilled counterparts, suggesting that they were better able to inhibit implausible competitors. On the other hand, skilled individuals on RAN (e.g., see Table 5) showed more interference than their less skilled counterparts, suggesting that they were less able to inhibit implausible competitors.

The pattern we observed with the comprehension composite suggests that individuals with more robust high-level comprehension skills are better able to inhibit implausible outcomes that share some features with predictable referents. This claim is consistent with previous findings reported by Gernsbacher and colleagues (Gernsbacher, 1993; Gernsbacher & Faust, 1991; Gernsbacher & Robertson, 1995). For example, Gernsbacher and Faust (1991) found that skilled comprehenders were better able to suppress the inappropriate meanings of homophones than less skilled comprehenders. They asked participants to read sentences like "He had lots of patients," in which the sentence-final word was a homophone (e.g., "patients" and "patience"), and to decide whether a probe word like "CALM" (which was related to this homophone's inappropriate meaning) matched the sentence's meaning. When "CALM" was presented immediately after the sentence-final word, all comprehenders were slow to reject "CALM" (vs. a control sentence like "He had lots of students"). However, when the probe was delayed by 1000 ms, only less skilled comprehenders continued to show this pattern. Gernsbacher and colleagues argue that "suppression" is a general cognitive mechanism that actively dampens irrelevant, inappropriate, and interfering information (e.g., the inappropriate meaning of a homophone; or a competing non-antecedent entity during anaphor resolution, as in Gernbacher, 1989). Moreover, they argue that skilled comprehenders have more efficient suppression mechanisms, allowing them to suppress the activation of "CALM" by the delayed time point.

The current results suggest that suppression mechanisms are not only important for the processing of homophony, but also for the prediction of linguistic outcomes. Indeed, variability in the efficiency of these mechanisms also appears to impact comprehenders' ability to suppress irrelevant, inappropriate, and interfering outcomes. Long and De Ley (2000) have also provided evidence that suppression is a *strategic* process, which comprehenders can suspend when relevant (e.g., undergraduate comprehenders were shown to not suppress nonreferents during dialogue processing, when there was considerable back-and-forth among referents). These data are compatible with the strategic nature of suppression: all of our sentences referred to predictable outcomes, and thus suppressing non-predictable outcomes provided a reasonable strategy in the current context.

On the other hand, the pattern we observed with RAN suggests a kind of tradeoff: rapid and automatic activation of information seems to facilitate prediction, as reflected in the activation of targets (see Fig. 3C), but also simultaneously drives the activation of competitors that share some features with the target (see Table 5). This latter pattern is reminiscent of Borovsky et al. (2013), who reported no evidence for interference from competitor objects in adolescents with SLI. They found that both SLI and typically developing (TD) listeners hearing "The dog chases…," while viewing a scene with a target CAT, competitor SHIP (which might be chased by a subject like pirate but not dog), and other distractors, fixated the CAT most. However, while TD listeners fixated the competitor SHIP more than distractors, SLI listeners showed no such effect. Similarly, we observed less interference in less skilled individuals on RAN. Although Borovsky and colleagues suggest that this may be due to limitations in cognitive resources of less skilled individuals, our findings do not support this claim. Rather, our data suggest that bottom-up interference depends on the rapid and automatic activation of lexical information, and that this interference may be reduced for individuals who are less speedy and/or automatic in activating this information.

3.3. Self-organization

Finally, our interest in the inhibition of implausible competitors again derives from the predictions of *self-organization* (e.g., Kukona & Tabor, 2011; Kukona et al., 2014; Tabor & Hutchins, 2004). Self-organization assumes that competitive dynamics among lower-level representations drives the activation of higher-level representations. Critically, these dynamics are predicted to give rise to interference effects from competitor objects. In other words, comprehenders are predicted to activate representations (e.g., WHITE CAR) that are supported by the input "locally" (e.g., the word "white") but not "globally" (e.g., the phrase "eat the white…"). Recent computational work by Kukona et al. (2014) also yields insight into individual differences in these effects. They implemented a self-organizing artificial neural network that modeled language comprehension in the visual world paradigm. It was trained to launch eye movements to visual objects that were referred to in its language input; for example, it was trained to activate WHITE CAKE when it heard "Eat [the] white cake." The network was "self-organizing" in that bidirectional connections among the network's (output) nodes allowed the system to converge on a coherent response to its input (e.g., "fixating" relevant visual objects). Across training, the network showed the following pattern: early on, interference from competitor objects was robust and prediction weak, but later on, interference was weak and prediction robust. Under the assumption that language skill (e.g., speed of processing/automaticity, or high-level comprehension) is dependent on experience (i.e., that the model late in training is analogous to a skilled individual), the network's behavior across training closely models the observed relation between prediction and inhibition, and the current pattern of individual differences (excepting RAN as it relates to WHITE CAR vs. BROWN CAR). Nevertheless, future computational work might also aim to address the effects of specific cognitive (sub)skills in prediction, rather than the effect of experience and/or training more generally. Helpfully, the currently results suggest that certain aspects of experience are more likely to be connected to prediction than others, such as those related to speed of processing, automation and/or comprehension (e.g., in contrast, measures related to print experience and working memory showed no relationship with prediction, even in our single predictor models). In this regard, Magnuson et al. (2011) have recently modeled individual differences in spoken word recognition (as reflected in the visual world paradigm) using a closely related self-organizing model, TRACE. They showed that competitor effects closely depended on lateral inhibition within the model.

Self-organization provides three further insights into these data. First, self-organization is a very general framework: self-organizing models, which converge on coherent sets of behaviors via feedback interactions, have addressed phenomena ranging from syntactic parsing (Tabor & Hutchins, 2004) to rhyme effects (e.g., Magnuson et al., 2011; see also related phenomenon outside of human cognition, e.g., Gordon, 2010; Keller & Segel, 1970; Marée & Hogeweg, 2001). Thus, self-organization may offer a *unifying* framework for capturing interactions between interference and language and literacy skill in a range of domains, including those investigated here and by Gernsbacher and colleagues. Second, self-organization may also offer a new perspective on the key role of inhibitory mechanisms in language comprehension. A critical assumption of self-organization is that *all* structure at *all* levels (e.g., phonological, lexical, syntactic, discourse, etc.) emerges from activation and inhibition (or suppression) dynamics. While self-organization predicts the diffuse activation of representations that only partially match the input, it also predicts that inhibition among these representations will drive the activation of the "best" representation, rather than a cacophony of activation. Thus, even predictive behaviors are assumed to depend on (lateral) inhibitory connections among competing outcomes in the self-organizing network described by Kukona et al. (2014). Consequently, pervasive effects of inhibition (and deficits in inhibition) on language comprehension, as observed here and in prior research, are precisely to be expected according to self-organization. Third, self-organization also provides a dynamical extension of accounts of global matching (e.g., Clark & Gronlund, 1996) that captures (e.g., the time course of) the dynamic interplay between targets and competitors, and the way that the language system can maintain equilibrium in the face of interference. For example, comprehenders *on average* demonstrated interference from the WHITE CAR on hearing "The boy will eat the white…," but this interference was transient and diminished over time as participants re-focused their eye movements on the predictable target (see Fig. 2). Likewise, this dynamic interplay is precisely to be expected given the activation and inhibition dynamics of self-organization.

One potential discrepancy between the current results and the predictions of self-organization concerns the relative timing of the predictive (i.e., WHITE CAKE) vs. interference (i.e., WHITE CAR) effects. In Kukona et al.'s (2014) model, these effects emerged concurrently; by contrast, in the current experiment the predictive effect seemed to precede the interference effect (i.e., compare the divergence of the red vs. blue curves to the purple vs. green curves in Fig. 2). In contrast to the predictions of Kukona et al.'s (2014) self-organizing model, this pattern may suggest that participants are strategically "checking" on competitors, or that competitors are being primed, *after* the target has been activated and/or fixated. Closer examination of only those trials in which participants were "predicting" (i.e., fixating the target WHITE CAKE by the end of the WHITE CAKE analysis window) revealed that during the noun (i.e., the WHITE CAR analysis window) the target WHITE CAKE was fixated in 85% of trials, the BROWN CAKE in 9%, the competitor WHITE CAR in 14%, and the distractor BROWN CAR in 2%. In comparison, examination of only those trials in which participants were *not* "predicting" revealed that during the noun the target WHITE CAKE was fixated in 83% of trials, the BROWN CAKE in 12%, the competitor WHITE CAR in 21%, and the distractor BROWN CAR in 7%. Thus, participants' behaviors were similar both in trials in which they did and did not show evidence of prediction (i.e., presumably, they would not be "checking" on competitors in the later case), with descending proportions of fixations to the WHITE CAKE, WHITE CAR, BROWN CAKE, and BROWN CAR. Additionally, there were numerically more fixations to the WHITE CAR in trials in which participants did not vs. did show evidence of prediction; neither pattern would appear consistent with the hypothesis that fixations to competitors depend on "checking." Alternatively, this pattern may simply reflect an issue of power: following the verb, eye movements to verb-inconsistent objects were *substantially* lower than to verb-consistent objects, and thus our ability to experimentally detect the competitor effect may similarly be substantially reduced (one avenue for future research may be to include a competitor condition without targets in the visual display).

The alternative approaches we have highlighted do not provide specific insight into this aspect of our data. For example, one prediction of the capacity-based approach (e.g., Just & Carpenter, 1992) is that comprehenders with larger capacities should show greater interference (e.g., as reflected in more eye movements to the WHITE CAR) due to their greater capacity to maintain information about multiple referents (see also Borovsky et al., 2013). We observed no such effect with our memory measures. Similarly, the experience-based approach of Mishra et al. (2012) does not directly address the inhibition of irrelevant, inappropriate, or interfering information; however, the claim that prediction is related to experience is broadly consistent with self-organization. Thus, while these approaches are interrelated with (and in some cases partially overlap with) self-organization, they do not provide a full account of the current findings.

In conclusion, we examined the role of language and literacy skills in the real-time prediction of linguistic outcomes. We observed considerable variation in comprehenders' ability to activate predictable outcomes, and inhibit implausible outcomes that shared some features with predictable referents. Our results suggest that this variation may be causally linked to differences in generalized processing speed (or automation of these processes) as gauged by measures of Rapid Automatized Naming and to differences in knowledge as reflected in measures of comprehension skill. These results provide new insight into the key (sub)skills that enable comprehenders to generate expectations about future linguistic input and outcomes, and launch predictive behaviors on the basis of these expectations.

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Appendix A

The individual difference measures that were included in our composites were submitted to an exploratory factor analysis with oblimin rotation and principal axis factoring. Kaiser's K1 rule and the minimum average partial (MAP) criteria suggested a four-factor solution, which accounted for 69% of the variance. Pattern matrix loadings are reported in Table A1. With one exception (Reading SDRT), the reading and listening comprehension and vocabulary measures loaded most strongly onto the first factor. Likewise, the phonological processing measures (from the CTOPP) loaded most strongly onto the first factor, although their loadings on this factor were considerably weaker than all but one of the previously mentioned comprehension and vocabulary measures. With one exception (Fluency WJ), the decoding and reading fluency measures loaded most strongly onto the second factor. By contrast, the RAN measures loaded most strongly onto the third factor. Finally, the print experience measures loaded most strongly onto the fourth factor.

This pattern supports our choice of composite measures. The first factor in the EFA best aligns with our comprehension composite. Our decision to retain a separate composite for phonological skills is theoretically motivated and also serves to avoid diluting potential associations of the general comprehension composite with performance on our experimental task. The second factor to emerge from the EFA aligns well with our decoding and fluency composite, the third with our RAN composite, and the fourth with our print experience composite. Additionally, while Reading SDRT and Fluency WJ loaded most strongly onto the fourth factor (vs. the first and second factors, respectively), their loadings are much weaker than those of the print experience measures (in fact, Reading SDRT loaded nearly as strongly onto the first factor as the fourth).

This result is broadly consistent with our theoretically motivated grouping of the measures (e.g., based on the constructs they were designed to assess) into comprehension, decoding and fluency, RAN, phonological skills, and print experience measures.

Table A1
Standardized factor loadings from the exploratory factor analysis of the individual difference measures included in the composite measures. The highest loading for each individual difference measure is indicated in bold.

	1	2	3	4
1. Reading GM	**0.62**	0.14	0.21	0.06
2. Reading PIAT	**0.87**	0.08	0.00	−0.14
3. Reading SDRT	0.42	0.05	0.11	**0.52**
4. Reading WJ	**0.59**	0.21	0.05	0.17
5. Listening PIAT	**0.87**	−0.03	−0.09	−0.04
6. Listening WJ	**0.78**	−0.19	0.18	0.16
7. Vocab PPVT	**0.83**	0.03	−0.04	0.16
8. Vocab WASI	**0.69**	0.06	−0.01	0.20
9. Decoding W TOWRE	0.05	**0.57**	0.29	0.20
10. Decoding W WJ	0.31	**0.61**	0.00	0.15
11. Decoding NW TOWRE	−0.05	**0.83**	0.15	0.07
12. Decoding NW WJ	0.03	**0.89**	−0.01	−0.09
13. Fluency GORT	0.14	**0.62**	0.05	0.22
14. Fluency WJ	0.23	0.20	0.16	**0.48**
15. RAN colors	0.05	−0.10	**0.73**	−0.16
16. RAN digits	0.01	0.18	**0.76**	0.05
17. RAN letters	−0.03	0.04	**0.89**	0.02
18. Phonological awareness	**0.60**	0.30	0.01	−0.15
19. Phonological memory	**0.45**	0.25	−0.03	−0.20
20. Print authors	0.06	0.08	0.03	**0.76**
21. Print magazines	0.02	0.10	−0.26	**0.58**

Table A2
Regression results for the single predictor simple linear regression analyses with all individual difference measures (i.e., not just the composites). Each β reflects a separate regression model.

	White vs. brown cake				White vs. brown car			
	β[a]	SE[a]	t	p	β[a]	SE[a]	t	p
1. Reading GM	2.95	1.05	2.80	<.01	−1.01	0.60	−1.69	.09
2. Reading PIAT	1.09	1.10	0.99	.33	−1.37	0.59	−2.32	<.05
3. Reading SDRT	2.63	1.07	2.46	<.05	−0.69	0.60	−1.14	.26
4. Reading WJ	2.64	1.06	2.48	<.05	−1.16	0.59	−1.96	.05
5. Listening PIAT	1.72	1.09	1.58	.12	−1.30	0.59	−2.21	<.05
6. Listening WJ	2.62	1.07	2.46	<.05	−1.10	0.60	−1.85	.07
7. Vocab PPVT	1.82	1.09	1.67	.10	−1.52	0.58	−2.61	<.05
8. Vocab WASI	1.70	1.09	1.56	.12	−1.35	0.59	−2.30	<.05
9. Decoding W TOWRE	2.88	1.06	2.73	<.01	0.10	0.61	0.16	.87
10. Decoding W WJ	1.36	1.10	1.24	.22	−0.32	0.61	−0.52	.60
11. Decoding NW TOWRE	3.21	1.04	3.08	<.01	−0.33	0.61	−0.54	.59
12. Decoding NW WJ	2.20	1.08	2.04	<.05	−0.94	0.60	−1.57	.12
13. Fluency GORT	1.22	1.10	1.11	.27	−0.44	0.61	−0.73	.47
14. Fluency WJ	3.73	1.02	3.68	<.001	−0.39	0.61	−0.64	.52
15. RAN colors	−2.70	1.06	−2.55	<.05	−1.34	0.59	−2.27	<.05
16. RAN digits	−3.94	1.00	−3.92	<.001	−0.39	0.61	−0.64	.53
17. RAN letters	−3.03	1.05	−2.88	<.01	−0.43	0.61	−0.70	.48
18. Phonological awareness	1.64	1.09	1.50	.14	−0.81	0.60	−1.35	.18
19. Phonological memory	1.86	1.09	1.71	.09	−0.28	0.61	−0.46	.65
20. Print authors	1.25	1.10	1.14	.26	−0.75	0.60	−1.23	.22
21. Print magazines	0.71	1.11	0.64	.52	0.01	0.61	0.01	.99
22. Working memory	1.46	1.10	1.33	.19	−0.47	0.61	−0.78	.44
23. Visuospatial memory	2.14	1.08	1.97	.05	0.32	0.61	0.53	.60
24. Matrix reasoning	2.48	1.07	2.31	<.05	−0.85	0.60	−1.41	.16
25. Saccade accuracy	1.62	1.09	1.48	.14	−0.16	0.61	−0.27	.79
26. Anti-sacc accuracy	1.87	1.09	1.72	.09	−0.37	0.61	−0.61	.54

[a] β and *SE* values $\times 10^{-2}$.

Appendix B

Single predictor models for all the individual difference measures (i.e., not just the composites). The analyses of difference scores in the verb-consistent cake conditions revealed a reliable intercept across all models (all *ts* > 5.11, all *ps* < .001). Similarly, the analyses of difference scores in the verb-inconsistent car conditions revealed a reliable intercept across all models (all *ts* > 7.90, all *ps* < .001). Effects of each of our individual difference measures are reported in Table A2.

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