AMERICAN PSYCHOLOGICAL ASSOCIATION

Journal of Experimental Psychology: General

ISSN: 0096-3445

2021, Vol. 150, No. 10, 2167–2174
https://doi.org/10.1037/xge0001042

BRIEF REPORT

Literacy Can Enhance Syntactic Prediction in Spoken Language Processing

Saoradh Favier[1], Antje S. Meyer[1], and Falk Huettig[1, 2]
[1] Department of Psychology of Language, Max Planck Institute for Psycholinguistics
[2] Centre for Language Studies, Radboud University

Language comprehenders can use syntactic cues to generate predictions online about upcoming language. Previous research with reading-impaired adults and healthy, low-proficiency adult and child learners suggests that reading skills are related to prediction in spoken language comprehension. Here, we investigated whether differences in literacy are also related to predictive spoken language processing in non-reading-impaired proficient adult readers with varying levels of literacy experience. Using the visual world paradigm enabled us to measure prediction based on syntactic cues in the spoken sentence, prior to the (predicted) target word. Literacy experience was found to be the strongest predictor of target anticipation, independent of general cognitive abilities. These findings suggest that (a) experience with written language can enhance syntactic prediction of spoken language in normal adult language users and (b) processing skills can be transferred to related tasks (from reading to listening) if the domains involve similar processes (e.g., predictive dependencies) and representations (e.g., syntactic).

Keywords: literacy, prediction, syntax

Supplemental materials: https://doi.org/10.1037/xge0001042.supp

Prediction has become the dominant theoretical framework for understanding the functioning of the mind and brain. In addition to playing an integral role in perception, action, and learning (Clark, 2013; Friston, 2005), the preactivation of predictable information is argued to reduce processing load and increase efficiency across multiple cognitive systems (e.g., Bar, 2003). Notably, psycholinguistic research increasingly emphasizes the importance of anticipatory mechanisms in language processing (for example, Altmann & Mirković, 2009; Dell & Chang, 2014; Federmeier, 2007; Ferreira & Chantavarin, 2018; Gibson et al., 2013; Hale, 2001; Hickok, 2012; Huettig, 2015; Kuperberg & Jaeger, 2016; Levy, 2008; Norris et al., 2016; Pickering & Gambi, 2018; Pickering & Garrod, 2013; Van Petten & Luka, 2012). However, most studies thus far have ignored the question of individual variation in predictive language processing (but see Federmeier et al., 2010; Hintz et al., 2017; Huettig & Janse, 2016; Kukona et al., 2016; Rommers et al., 2015).

The determinants (and extent) of individual differences in anticipatory language processing may offer important insights about the role and mechanisms of prediction in language and cognition more generally. There is now mounting evidence to suggest that individual variation in reading skills may be an important factor, even in anticipatory spoken language processing. Studies with reading-impaired adults (Huettig & Brouwer, 2015), healthy low-proficiency adults (Mishra et al., 2012), and child learners (Mani & Huettig, 2014) provide converging evidence that reading skills have a bearing on prediction in spoken language. But are these effects the hallmark of an impaired/developing system or are they a general feature of proficiency transfer between two related domains (reading and speech prediction)? This is an important question because it promises to illuminate the relationship between predictive processing and proficiency within a given domain as well as the transfer of training/experience between related domains. Such near transfer effects have previously been demonstrated, for example, between working memory and reading comprehension (Karbach et al., 2015; Novick et al., 2014).

Here, we aimed to address these issues by investigating prediction in language processing (defined as the preactivation of linguistic representations before incoming bottom-up input has had a chance to activate them; Huettig, 2015) in non-reading-impaired healthy adults with varying levels of literacy experience. One previous study provides some tentative evidence. Ng et al. (2018)

This article was published Online First June 17, 2021.

Falk Huettig https://orcid.org/0000-0001-9135-4178

Data and stimuli are available on the Open Science Framework (osf.io/pds4w). There has been no prior dissemination of the specific idea or data that appear in this article.

Correspondence concerning this article should be addressed to Falk Huettig, Department of Psychology of Language, Max Planck Institute for Psycholinguistics, P.O. Box 310, 6500 AH Nijmegen, the Netherlands. Email: falk.huettig@mpi.nl

asked a community sample of adults with varying literacy levels to listen to spoken sentences. Proficient readers showed a reduced event-related potential (ERP) negativity for strongly predictable target words over anterior channels, in a time window from 170 to 300 ms after target word onset, but the same ERP response was not found in less-skilled readers. Neural correlates of prediction measured on the target word (and not before), however, can be explained by a number of other (nonpredictive) accounts, such as differences in the integration of nonpredicted representations (for further discussion see Baggio & Hagoort, 2011; Huettig, 2015; Mantegna et al., 2019; Nieuwland et al., 2018, 2020).

In the present study, we chose to investigate syntactic prediction because syntactic proficiency is expected to increase with literacy experience. Readers are exposed to a rich syntactic environment that is considerably more complex and diverse than typical conversational speech. Written narratives contain 60% more instances of subordination than speech (Kroll, 1977), and relatively infrequent structures like passives, object relative clauses, and participial phrases are predominantly attested in written corpora (e.g., Roland et al., 2007). The impact of written language exposure on syntactic proficiency has been demonstrated both for comprehension (Langlois & Arnold, 2020; Street & Daôbrowska, 2010) and production (Montag & MacDonald, 2015) in children and adults (e.g., Crain-Thoreson & Dale, 1992; Daôbrowska, 2018). Several studies have investigated syntactic prediction (e.g., Arai & Keller, 2013; Chen et al., 2005; Kamide et al., 2003; Staub & Clifton, 2006), but (to the best of our knowledge) none assessed the influence of reading experience on syntactic anticipation in healthy literate adults.

Here, we used the visual world paradigm to measure eye gaze as a straightforward marker of prediction. We asked Dutch adults with high- and low-literacy experience to listen to passive sentences such as "Het raam wordt inderdaad gebroken door een stier [The window is indeed broken by a bull]" in conjunction with visual displays such as Figure 1.

The auxiliary *wordt* is an early but unreliable indicator of passive voice because it could also be parsed as an intransitive main verb (e.g., "Hij wordt rijk [He gets rich]"). Only at the participle (*gebroken*) can the grammatical function of *wordt* be disambiguated and the preverbal argument (*Het raam*) be assigned the role of patient. In other words, there is sufficient information at the participle to parse the unfolding sentence as passive and to predict that a prepositional complement specifying the agent may follow. The preposition door, *by*, provides the final and unequivocal cue to expect an agent.

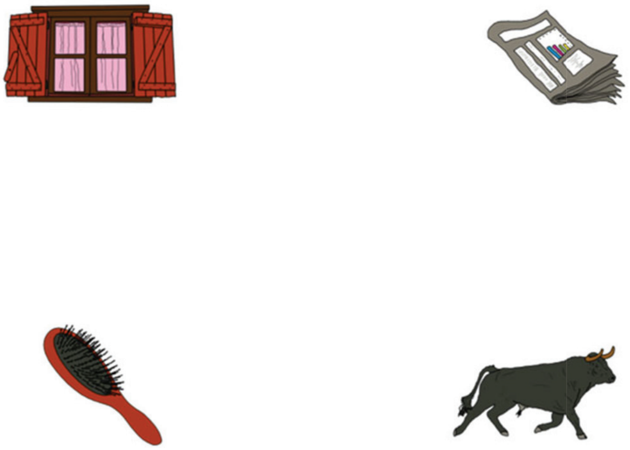
Method

Participants

Thirty-eight native Dutch speakers volunteered to participate in the experiment (*M* age = 25.2 years; 25 female). We recruited from a pool of 161 participants with varying degrees of literacy experience who had completed a battery of individual difference measures as part of a different study (Favier & Huettig, in press). We performed a preregistered principal components analysis on six literacy measures (receptive vocabulary, author recognition, reading habits, spelling, word, and pseudoword reading) to derive an underlying construct that explained the maximal amount of variance in the literacy data (literacy PC1 in Table 1).[1] For the current study, we tested all participants in the top and bottom quartiles for the literacy PC1 who responded to our invitation for the eye-tracking experiment. Whereas this constrained the ultimate sample size, the potential to observe an effect of literacy experience was increased by our extreme-groups design. In addition, the sample size (N = 38) is similar to previous visual world studies that observed syntactic prediction effects with 30–40 participants (Arai & Keller, 2013; Kamide et al., 2003). One participant was excluded because the eye tracker failed to calibrate to the eyes. There is a pronounced group difference in literacy experience, based on literacy PC1 ($t = 8.70$, $p < .001$). The small difference in nonverbal IQ (Raven's) scores between high- (HLE) and low-literacy experience (LLE) groups ($t = 2.10$, $p = .04$) was expected and is in line with previous research (e.g., Hervais-Adelman et al., 2019; Olivers et al., 2014; Skeide et al., 2017). The groups did not differ significantly in age ($t = 1.79$, $p = .09$). Because literacy PC1 was measured 18–24 months prior to the current study, we readministered the Author Recognition Test (Brysbaert et al., 2013; Stanovich & West, 1989) to account for change in literacy experience over time that could affect the size of the group difference. Author Recognition Test scores remained significantly higher in the HLE group ($t = 4.01$, $p < .001$).

Figure 1

Example Visual Display for the (Passive) Spoken Sentence, "Het Raam Wordt Inderdaad Gebroken Door een Stier [The Window Is Indeed Broken by a Bull]," in Which "Stier" is the Target Picture



Note. Distractors were always inanimate objects, and none were plausible agents of the events described. There were no statistical differences in mean frequency of picture labels (Table 2) in the four sets of pictures (F = 0.09, p = .97). Picture positions were pseudorandomized such that patient and target entities appeared equally often in all four positions on the visual display. There was no repetition of pictures in the experiment. See the online article for the color version of this figure.

---

[1] A more detailed description of the tests used, the principal components analysis, and other further analyses, as well as the data, are available at https://osf.io/pds4w/?view_only=cc7a95d3b0414b2e8e86a86eda0a5d10.

Table 1

Descriptive Summary of High- and Low-Literacy Experience Groups

Literacy experience	*n*	Age	Literacy PC1 score	Nonverbal IQ	Verbal WM
High	20	26.10 (4.41)	1.50 (.89)	22.30 (6.11)	7.30 (2.20)
Low	18	24.16 (1.89)	−1.69 (1.30)	18.28 (5.72)	8.39 (2.68)

Note. PC1 = first principal component; WM = working memory. Group means are based on raw scores for individual difference measures (except literacy PC1, a derived score). Standard deviations are shown in parentheses. Nonverbal IQ and verbal working memory were assessed using Raven's progressive matrices and the backward digit span task, respectively.

Materials

Twenty-four Dutch passive sentences were constructed by combining a set of 12 transitive verbs with 24 inanimate patients (objects) and 24 animate agents (animals) such that each verb was presented twice. Our aim was to assess syntactic prediction; thus, we avoided object-animal pairings with salient semantic associations (e.g., *shoe-dog*) in favor of less typical combinations (e.g., *paintbrush-dog*).[2] All experimental sentences used the present-tense passive frame as in "Het raam wordt inderdaad gebroken door een stier [The window is indeed broken by a bull]," that is, patient + present passive auxiliary + adverb + participle + preposition + agent. The adverb *inderdaad* (*indeed*) served as padding to ensure sufficient power to detect potential syntactic prediction effects. Each experimental sentence was paired with a visual display, comprising four color pictures (see Table 2) from the MultiPic database (Duñabeitia et al., 2018): an inanimate entity (the patient), an animate entity (the agent, henceforth the target), and two semantically unrelated distractors (see Figure 1).

In addition, 60 filler items using intransitive verbs (e.g., "De caravan staat inderdaad best ver weg van de molen [The caravan is indeed quite far away from the windmill]") were constructed. A subset of 14 fillers was used as reference items to provide a by-participant experimental baseline for lexical processing speed. We constructed the reference items such that the sentence-final entity (the target) could not easily be predicted from either the sentence context or the pictures in the visual display (see Figure 2). Auditory stimuli were recorded in a soundproofed booth by a female native Dutch speaker, using a Sennheiser ME64 microphone. The recording was sampled at 44 kHz (mono) with 16-bit sampling resolution.

Procedure

Participants were tested individually in a soundproofed experiment booth. An SR Research EyeLink 1000 tower-mounted eye tracker (Ottawa, Canada), was used to record eye movements. Participants were instructed to avoid moving their eyes away from the screen and to listen carefully to the sentences presented via headphones (a well-established protocol, particularly in experiments on prediction in language processing; see Huettig et al., 2011, for further discussion).

Each trial began with a 1-s central fixation, followed by a visual display. There was a 2-s preview of the pictures before the onset of the cue (*wordt*) in the speech signal. The pictures remained on the screen until 2,500 ms after the onset of the target word. The mean duration of the critical window between cue and target onset was 2,005 ms in passive trials and 2,162 ms in reference trials (here, the cue was defined as the verb, e.g., *lijkt* [*seems*]). There were 84 trials in total, of which 29% were passive and 71% were fillers. The order of trials was automatically pseudorandomized for each participant (with a maximum of two consecutive passive trials). The experiment took approximately 20 min, including calibration.

Table 2

Descriptive Summary of Log10 Word Frequency Values for Experimental Picture Labels, Grouped by Set

Picture set	Patient	Target	Distractor 1	Distractor 2
Log10 frequency, *M* (*SD*)	2.64 (.86)	2.57 (.60)	2.60 (.68)	2.54 (.82)

Note. The picture labels are grouped by set (SUBTLEX-NL).

Results

Eyelink DataViewer was used to code fixations, saccades, and blinks. Data from four of 888 experimental trials were missing because of track loss. Fixation locations were coded automatically with respect to predefined regions of the visual display: patient, target, distractor 1, distractor 2, and background (i.e., none of the pictures). In the HLE group, 2% of fixations on experimental trials were coded as background. One participant in the low literacy experience (henceforth LLE) group was excluded because of 79% background fixations. For the remaining LLE group (n = 17), the rate of background fixations was 2%. Figure 3 shows the averaged fixation proportions to the target, patient, and averaged distractors on passive trials for HLE (Panel A) and LLE groups (Panel B), as well as a difference score, that is, the time course of target preference for each group (Panel C). Visual inspection of the plots suggests that the HLE group anticipated the target earlier than the LLE group (see Table 3 for group means).

The 14 nonpredictive reference items were analyzed to provide a baseline for lexical processing speed. This was indexed as the log odds of fixating the target entity in the first 500 ms after target word onset (with 200-ms adjustment), averaged across reference items. The mean rate of target fixations during this window was 35% (SD = 11%) for the HLE group and 30% (SD = 12%) for the LLE group, indicating a relatively small group difference. The empirical logit function (Barr, 2008) was used to transform individuals' average target gaze durations to log odds, providing a participant-level index of lexical processing speed.

---

[2] The semantic relatedness of patients and agents (indexed as cosine distance) was similar to that of patients and distractors (F = 1.15, p = .32). Cosine distances between verbs and targets versus verbs and distractors also did not differ significantly (F = 1.16, p = .32). The full set of visual stimuli for passive trials is reported in the online supplemental materials.

Figure 2

Example Filler Visual Display for the Spoken Sentence, "De Vlinder Lijkt Inderdaad Veel Kleiner Dan een Dolfijn [The Butterfly Indeed Seems Much Smaller Than a Dolphin]," in Which the Unpredictable Target Word is "Dolfijn"

Note. See the online article for the color version of this figure.

To analyze the amount of variance in anticipatory eye movements that could be explained by literacy experience, we fit a linear mixed-effects model (see Table 4) to the eye-tracking data from passive trials, using the lme4 package in R Version 1.2.1335 (Bates et al., 2014; R Core Team, 2019). The dependent variable was calculated for the predictive period between the acoustic onset of *wordt* and the onset of the target noun (+200 ms). We first aggregated gaze durations by participant, item, and display region and then transformed the durations to log odds using the empirical logit function. Finally, the averaged log odds of looks to the two distractors was subtracted from the log odds of looks to the target. Our dependent variable was the resulting difference score, which indicates the strength of target preference. Literacy experience group (LLE/HLE) was a fixed factor in the model, with LLE treated as the reference level.[3] The model contained lexical processing speed (calculated as described above and mean centered), and its interaction with literacy experience group, to account for the possibility that efficiency of word-object mapping mediated any literacy effect. To evaluate the contribution of literacy PC1 that was independent of general cognitive abilities, we also included nonverbal IQ and verbal working memory scores (mean centered). Finally, we added random intercepts for participants and items. Statistically confirming the divergent trajectories shown in Figure 3 (Panel C), target preference was stronger in the HLE than LLE group (a conclusion also supported by growth curve analysis; see online supplemental materials). There was no robust evidence for an interaction between literacy experience and lexical processing speed or for a main effect of lexical processing speed on target preference. Finally, the results indicate that nonverbal IQ and verbal working memory contributed little to anticipatory eye movements.

Discussion

The present results corroborate previous findings that language comprehenders can use syntactic cues to generate predictions online about upcoming language (e.g., Arai & Keller, 2013; Chen et al., 2005; Kamide et al., 2003; Staub & Clifton, 2006). More importantly, the current study presents the first clear experimental evidence from non-reading-impaired adults that syntactic prediction in spoken language comprehension is related to adults' literacy experience.[4] The eye-tracking method used here enabled us to measure syntactic prediction in speech processing unequivocally (i.e., before participants heard the anticipated target). Literacy experience emerged as the strongest predictor of target (i.e., agent) preference, independent of general cognitive abilities. The main effect of literacy experience on anticipatory eye movements in our study echoes previous observations of reading-related differences in spoken language prediction based on other types of information (e.g., semantic representations, Mani & Huettig, 2014; grammatical gender, Huettig & Brouwer, 2015).

There are a number of alternative explanations of the present literacy-related syntactic prediction effect that can be rejected. First, one may argue that the group difference in anticipatory eye movements simply reflects slower word-object mapping in less-experienced literates because language experience has previously been linked to the efficiency of language-mediated looking (e.g., James, 2014; Mishra et al., 2012). We designed a baseline measure of lexical processing speed to address this potential confound and observed evidence neither for an interaction between literacy experience and lexical processing speed nor for a main effect of lexical processing speed on target preference. Second, one may suggest that differences in prediction simply reflect general ability (*g*-factor) differences that are measured by intelligence tests rather than differences in literacy experience. We can also reject this alternative explanation. Previous research has found that increased literacy and education results in small increases in Raven's scores (e.g., Hervais-Adelman et al., 2019; Olivers et al., 2014; Skeide et al., 2017). Moreover, the minimal contribution of nonverbal IQ in our results is consistent with previous findings that Raven's performance explains very little unique variance in language-mediated prediction (Hintz et al., 2017; Huettig & Janse, 2016; Rommers et al., 2015).

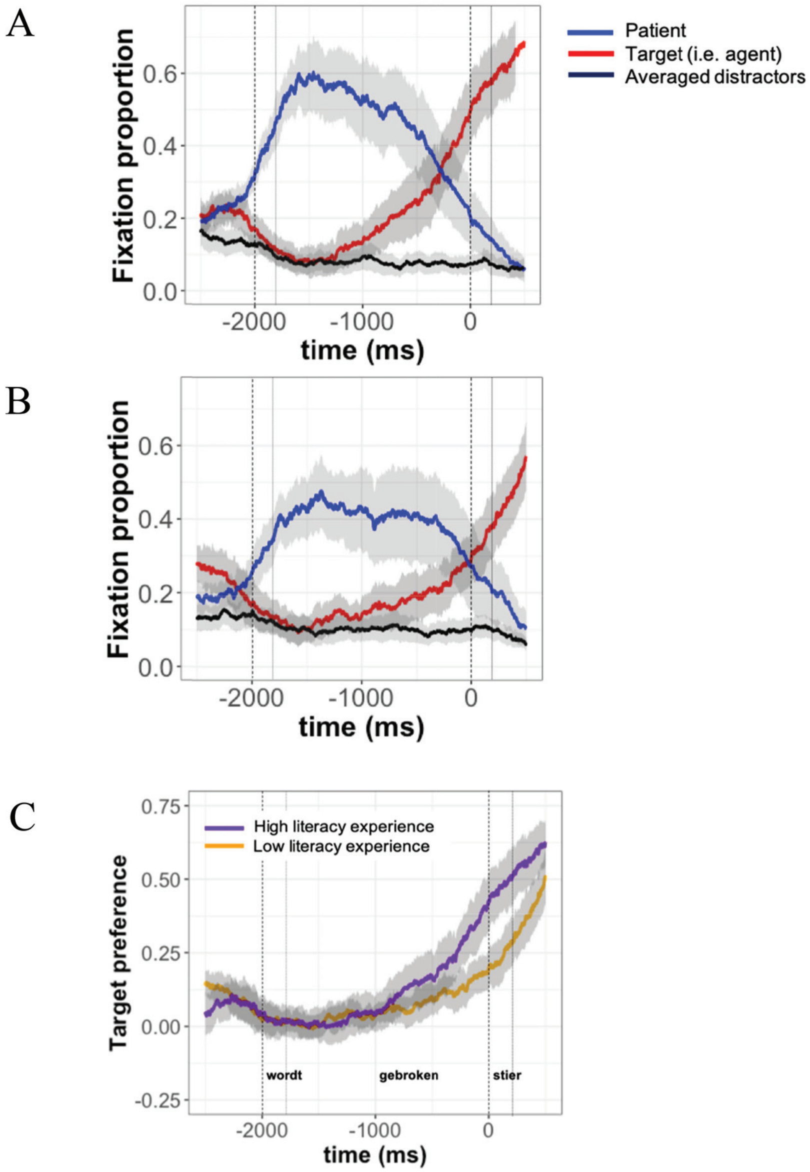
---

[3] Descriptive model comparison indicated a better fit for the model with literacy experience as a categorical (AIC = 4,694.1) versus continuous predictor (AIC = 4,698.3).

[4] Note that typically developed Dutch adults have no difficulties understanding Dutch passive sentences. Even Dutch-speaking 5-year-olds interpreted full passive sentences in an auditory sentence-picture-matching task with (for this age group) very high accuracy (average 82.3%; Armon-Lotem et al., 2016). On reviewer request, we analyzed existing behavioral data from 112 adult native Dutch speakers (aged 18–35 years and diverse in terms of education and ability) who took part in a different study at Max Planck Institute, Nijmegen. This study administered a large battery of individual difference measures, including the Author Recognition Test, and an auditory sentence-picture-matching task that assessed comprehension of (among others) the passive construction. Our analysis of the raw data for passive trials revealed an overall accuracy rate of 99.29%. We examined a subset of 28 participants with Author Recognition Test scores in the bottom quartile (i.e., comparable with our LLE group) and found that their performance on passive sentences was at ceiling (100% accuracy). Although these were not the same as the sentences used for current study, the use of reversible passives in that study (e.g., "De man wordt gekust door het meisje [The man is being kissed by the girl]") makes their stimuli more challenging than the nonreversible passives we used (e.g., "De watermeloen wordt inderdaad geschopt door een ezel [The watermelon is indeed kicked by a donkey]").

Figure 3

The Time Window of Interest Extended From the Acoustic Onset of "Wordt" to the Onset of the Target Word (Time Zero), Both Adjusted by 200 ms to Account for the Time Taken to Program and Launch a Language-Mediated Saccadic Eye Movement (Saslow, 1967)



Note. Panel A plots fixation proportions to patient, target, and averaged distractor entities for the HLE group (n = 19). Panel B plots fixation proportions to the same entities for the low-literacy experience group (n = 18). Panel C plots the difference between target and distractor fixations (i.e., target preference) by group calculated by subtracting the proportion of averaged distractor fixations from the proportion of target fixations at each time step. Patient fixations were not included in this calculation. A target preference of zero means that the target and averaged distractors were fixated equally often, whereas values greater than zero reflect relatively more fixations to the target. The gray shaded areas represent by-participant 95% confidence intervals, computed at each 1-ms sampling step (Masson & Loftus, 2003). Vertical dashed lines indicate the acoustic onsets of *wordt* (M = −2,005) and the target word (time zero). Vertical dotted lines represent a +200-ms adjustment to onset times, reflecting the typical latency of language-mediated eye movements. In Panel C, the approximate onset of the participle in the speech signal (M = −1,003 ms) is indicated by *gebroken*. See the online article for the color version of this figure.

Table 3

M Fixation Proportions (Passive Trials) to the Target, Averaged Distractors, and the M Difference Between Them (Target Fixations Minus Averaged Distractor Fixations) as Well as M Fixation Proportions to the Background for the High- (HLE) and Low- (LLE) Literacy Experience Groups During the Critical Time Window (200 ms After "Wordt" Onset Until 200 ms After Target Onset)

Group	Target	Averaged distractors	Mean difference	Background
HLE	.23 (.22)	.08 (.09)	.15 (.24)	.02 (.08)
LLE	.19 (.21)	.11 (.10)	.08 (.24)	.02 (.07)

Note. Standard deviations are provided in parentheses.

Literacy and Prediction

How does literacy experience influence syntactic prediction in spoken language processing? It is useful to distinguish between primary and secondary influences of reading experience, both of which affect the core processes and representations that are common to written and spoken language (Huettig & Pickering, 2019). Secondary influences arise from exposure to book language, which is syntactically more elaborate (with higher demands on verbal memory) and lexically more extensive and sophisticated than conversational speech. Secondary influences can be attained not only through reading but also through listening to book-like auditory materials (e.g., audiobooks). It has been shown that the amount of shared book reading with parents at 24 months predicts children's auditory comprehension of syntactically complex sentences at 30 months (Crain-Thoreson et al., 2001). Moreover, for children and adults alike, literacy results in both increased vocabulary knowledge (Cain & Oakhill, 2011; Cunningham & Stanovich, 1991) and verbal working memory (Démoulin & Kolinsky, 2016; Smalle et al., 2019).

Primary influences are more directly linked to the physical act of reading (for example, efficient decoding of written language; increased exposure to the extreme form invariance of printed word forms; parallel processing of multiple letters/words in proficient readers; see Huettig & Pickering, 2019, for further discussion). The present results cannot conclusively distinguish between primary and secondary influences of reading on spoken language prediction because our (statistically determined) literacy PC1 contained both primary (word and pseudoword reading, spelling, abilities) and secondary (receptive vocabulary, author recognition) characteristics of reading. That being said, the likely higher frequency of the Dutch passive construction in book language than informal speech (based on comparative corpus data for English; Roland et al., 2007) is most consistent with a secondary effect of literacy experience on predictive processing. It is also noteworthy that verbal working memory contributed very little to the observed anticipatory eye movements (cf. Huettig & Janse, 2016). To further assess causality and the individual contributions of primary and secondary influences of reading on (syntactic) prediction, a large-scale study with a longitudinal design would be useful.

To sum up, the present study strongly suggests that proficiency is important for predictive processing: Literacy experience enhances anticipation of upcoming language. Strikingly, experience with written language enhances syntactic prediction of spoken language in normal adult language users. Theories of prediction in language processing, and in cognitive science more generally, must be adapted to reflect more clearly that prediction is contingent on experience not only at the task at hand (e.g., spoken language processing) but also at related ones (e.g., reading). Processing skills transfer to related tasks if the domains involve similar processes (e.g., predictive dependencies) and representations (e.g., syntactic).

Context of the Research

Prediction has become a very influential theoretical construct of how the human mind works. The idea for this study originated in the research program of Falk Huettig, which explores how predictive processing is related to proficiency with the task at hand. This research had previously shown that reading-impaired adults, healthy low-proficiency adult readers in India, and child learners predict upcoming spoken language less than more literate children and adults. Here, we investigated whether these effects are a hallmark of an impaired or developing system or a general characteristic of language processing. We observed that literacy experience in healthy Dutch adults was the strongest predictor of (syntactic) target anticipation, independent of general cognitive abilities. This shows that proficiency is important for predictive processing and suggests that training/experience in one domain (reading in this case) transfers to a related domain (speech prediction). We plan to extend this research by teasing apart primary (directly linked to the physical act of reading, e.g., written language decoding, extreme form invariance of printed words) from secondary (also attained by listening to book language such as audio books, e.g., enhanced vocabulary knowledge and working memory) influences of reading on the prediction of spoken language. Ultimately, we want to know whether predictions are 'just' a natural byproduct of efficient access and processing of mental representations (rather than the deep goal of processing, in line with theories that consider the human mind to be a predictive engine).

Table 4

Summary of Fixed Effects in Liner Mixed-Effects Model

Predictor	Coefficient	*SE*	*t* value	95% CI
Intercept	1.24	0.38	3.25	[0.49, 1.99]
Literacy experience, high	1.16	0.56	2.06	[0.06, 2.26]
Lexical processing speed	0.13	0.52	0.24	[−0.89, 1.14]
Nonverbal IQ	0.02	0.05	0.37	[−0.07, 0.11]
Verbal working memory	0.07	0.10	0.69	[−0.13, 0.27]
Literacy Experience, High × Lexical Processing Speed	0.53	0.90	0.59	[−1.22, 2.29]

Note. $N = 837$. *SE* = standard error; CI = confidence interval. The intercept represents target preference (log odds of fixating target minus log odds of fixating distractors) for a participant in the LLE group with average lexical processing speed, nonverbal IQ, and verbal working memory. The positive intercept reflects the LLE group's relatively higher odds of fixating the target versus the distractors (i.e., target preference) during the critical time window.

References

Altmann, G. T., & Mirković, J. (2009). Incrementality and prediction in human sentence processing. *Cognitive Science*, *33*(4), 583–609. https://doi.org/10.1111/j.1551-6709.2009.01022.x

Arai, M., & Keller, F. (2013). The use of verb-specific information for prediction in sentence processing. *Language and Cognitive Processes*, *28*(4), 525–560. https://doi.org/10.1080/01690965.2012.658072

Armon-Lotem, S., Haman, E., Jensen de López, K., Smoczynska, M., Yatsushiro, K., Szczerbinski, M., van Hout, A., Dabašinskienė, I., Gavarró, A., Hobbs, E., Kamandulytė-Merfeldienė, L., Katsos, N., Kunnari, S., Nitsiou, C., Sundahl Olsen, L., Parramon, X., Sauerland, U., Torn-Leesik, R., & van der Lely, H. (2016). A large-scale cross-linguistic investigation of the acquisition of passive. *Language Acquisition*, *23*(1), 27–56. https://doi.org/10.1080/10489223.2015.1047095

Baggio, G., & Hagoort, P. (2011). The balance between memory and unification in semantics: A dynamic account of the N400. *Language and Cognitive Processes*, *26*(9), 1338–1367. https://doi.org/10.1080/01690965.2010.542671

Bar, M. (2003). A cortical mechanism for triggering top-down facilitation in visual object recognition. *Journal of Cognitive Neuroscience*, *15*(4), 600–609. https://doi.org/10.1162/089892903321662976

Barr, D. J. (2008). Analyzing 'visual world' eyetracking data using multilevel logistic regression. *Journal of Memory and Language*, *59*(4), 457–474. https://doi.org/10.1016/j.jml.2007.09.002

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *ArXiv*. http://arxiv.org/abs/1406.5823

Brysbaert, M., Mandera, P., & Keuleers, E. (2013). *Naambekendheid Van Fictieschrijvers in Vlaanderen: Resultaten Van de Auteurstest* [Dutch Author Recognition Test]. https://biblio.ugent.be/publication/4268783/file/4268798

Cain, K., & Oakhill, J. (2011). Matthew effects in young readers: Reading comprehension and reading experience aid vocabulary development. *Journal of Learning Disabilities*, *44*(5), 431–443. https://doi.org/10.1177/0022219411410042

Chen, E., Gibson, E., & Wolf, F. (2005). Online syntactic storage costs in sentence comprehension. *Journal of Memory and Language*, *52*(1), 144–169. https://doi.org/10.1016/j.jml.2004.10.001

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences*, *36*(3), 181–204. https://doi.org/10.1017/S0140525X12000477

Crain-Thoreson, C., Dahlin, M. P., & Powell, T. A. (2001). Parent-child interaction in three conversational contexts: Variations in style and strategy. *New Directions for Child and Adolescent Development*, *92*, 23–38.

Crain-Thoresen, C., & Dale, P. S. (1992). Do early talkers become early readers? Linguistic precocity, preschool language, and emergent literacy. *Developmental Psychology*, *28*(3), 421–429. https://doi.org/10.1037/0012-1649.28.3.421

Cunningham, A. E., & Stanovich, K. E. (1991). Tracking the unique effects of print exposure in children: Associations with vocabulary, general knowledge, and spelling. *Journal of Educational Psychology*, *83*(2), 264–274. https://doi.org/10.1037/0022-0663.83.2.264

Daôbrowska, E. (2018). Experience, aptitude and individual differences in native language ultimate attainment. *Cognition*, *178*, 222–235. https://doi.org/10.1016/j.cognition.2018.05.018

Dell, G. S., & Chang, F. (2014). The P-chain: Relating sentence production and its disorders to comprehension and acquisition. *Philosophical Transactions of the Royal Society of London Series B: Biological Sciences*, *369*(1634), Article 20120394. https://doi.org/10.1098/rstb.2012.0394

Démoulin, C., & Kolinsky, R. (2016). Does learning to read shape verbal working memory? *Psychonomic Bulletin & Review*, *23*(3), 703–722. https://doi.org/10.3758/s13423-015-0956-7

Duñabeitia, J. A., Crepaldi, D., Meyer, A. S., New, B., Pliatsikas, C., Smolka, E., & Brysbaert, M. (2018). MultiPic: A standardized set of 750 drawings with norms for six European languages. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *71*(4), 808–816. https://doi.org/10.1080/17470218.2017.1310261

Favier, S., & Huettig, F. (in press). Long-term written language experience affects syntactic awareness and usage but not syntactic priming of spoken sentences. *Quarterly Journal of Experimental Psychology*.

Federmeier, K. D. (2007). Thinking ahead: The role and roots of prediction in language comprehension. *Psychophysiology*, *44*(4), 491–505. https://doi.org/10.1111/j.1469-8986.2007.00531.x

Federmeier, K. D., Kutas, M., & Schul, R. (2010). Age-related and individual differences in the use of prediction during language comprehension. *Brain and Language*, *115*(3), 149–161. https://doi.org/10.1016/j.bandl.2010.07.006

Ferreira, F., & Chantavarin, S. (2018). Integration and prediction in language processing: A synthesis of old and new. *Current Directions in Psychological Science*, *27*(6), 443–448. https://doi.org/10.1177/0963721418794491

Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society of London Series B: Biological Sciences*, *360*(1456), 815–836. https://doi.org/10.1098/rstb.2005.1622

Gibson, E., Bergen, L., & Piantadosi, S. T. (2013). Rational integration of noisy evidence and prior semantic expectations in sentence interpretation. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(20), 8051–8056. https://doi.org/10.1073/pnas.1216438110

Hale, J. (2001). A probabilistic early parser as a psycholinguistic model. *Proceedings of the second meeting of the North American Chapter of the Association for Computational Linguistics on Language Technologies* (pp. 1–8). Association for Computational Linguistics. https://doi.org/10.3115/1073336.1073357

Hervais-Adelman, A., Kumar, U., Mishra, R. K., Tripathi, V. N., Guleria, A., Singh, J. P., Eisner, F., & Huettig, F. (2019). Learning to read recycles visual cortical networks without destruction. *Science Advances*, *5*(9), Article eaax0262. https://doi.org/10.1126/sciadv.aax0262

Hickok, G. (2012). Computational neuroanatomy of speech production. *Nature Reviews Neuroscience*, *13*(2), 135–145. https://doi.org/10.1038/nrn3158

Hintz, F., Meyer, A. S., & Huettig, F. (2017). Predictors of verb-mediated anticipatory eye movements in the visual world. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(9), 1352–1374. https://doi.org/10.1037/xlm0000388

Huettig, F. (2015). Four central questions about prediction in language processing. *Brain Research*, *1626*, 118–135. https://doi.org/10.1016/j.brainres.2015.02.014

Huettig, F., & Brouwer, S. (2015). Delayed anticipatory spoken language processing in adults with dyslexia—Evidence from eye-tracking. *Dyslexia*, *21*(2), 97–122. https://doi.org/10.1002/dys.1497

Huettig, F., & Janse, E. (2016). Individual differences in working memory and processing speed predict anticipatory spoken language processing in the visual world. *Language, Cognition and Neuroscience*, *31*(1), 80–93. https://doi.org/10.1080/23273798.2015.1047459

Huettig, F., Olivers, C. N. L., & Hartsuiker, R. J. (2011). Looking, language, and memory: Bridging research from the visual world and visual search paradigms. *Acta Psychologica*, *137*(2), 138–150. https://doi.org/10.1016/j.actpsy.2010.07.013

Huettig, F., & Pickering, M. J. (2019). Literacy advantages beyond reading: Prediction of spoken language. *Trends in Cognitive Sciences*, *23*(6), 464–475. https://doi.org/10.1016/j.tics.2019.03.008

James, A. (2014). *Reading experience predicts eye movements during online auditory comprehension* [Master thesis]. University of Illinois at Urbana-Champaign. https://www.ideals.illinois.edu/bitstream/handle/2142/50596/Ariel_James.pdf?sequence=1

Kamide, Y., Scheepers, C., & Altmann, G. T. M. (2003). Integration of syntactic and semantic information in predictive processing: Cross-linguistic evidence from German and English. *Journal of Psycholinguistic Research*, *32*(1), 37–55. https://doi.org/10.1023/A:1021933015362

Karbach, J., Strobach, T., & Schubert, T. (2015). Adaptive working-memory training benefits reading, but not mathematics in middle childhood. *Child Neuropsychology*, *21*(3), 285–301. https://doi.org/10.1080/09297049.2014.899336

Kroll, B. (1977). Combining ideas in written and spoken English: Discourse across time and space. In E. O. Keenan & T. L. Bennett (Eds.), *Discourse across time and space* (pp. 69–108). University of Southern California.

Kukona, A., Braze, D., Johns, C. L., Mencl, W. E., Van Dyke, J. A., Magnuson, J. S., Pugh, K. R., Shankweiler, D. P., & Tabor, W. (2016). The real-time prediction and inhibition of linguistic outcomes: Effects of language and literacy skill. *Acta Psychologica*, *171*, 72–84. https://doi.org/10.1016/j.actpsy.2016.09.009

Kuperberg, G. R., & Jaeger, T. F. (2016). What do we mean by prediction in language comprehension? *Language, Cognition and Neuroscience*, *31*(1), 32–59. https://doi.org/10.1080/23273798.2015.1102299

Langlois, V. J., & Arnold, J. E. (2020). Print exposure explains individual differences in using syntactic but not semantic cues for pronoun comprehension. *Cognition*, *197*, Article 104155. https://doi.org/10.1016/j.cognition.2019.104155

Levy, R. (2008). Expectation-based syntactic comprehension. *Cognition*, *106*(3), 1126–1177. https://doi.org/10.1016/j.cognition.2007.05.006

Mani, N., & Huettig, F. (2014). Word reading skill predicts anticipation of upcoming spoken language input: A study of children developing proficiency in reading. *Journal of Experimental Child Psychology*, *126*, 264–279. https://doi.org/10.1016/j.jecp.2014.05.004

Mantegna, F., Hintz, F., Ostarek, M., Alday, P. M., & Huettig, F. (2019). Distinguishing integration and prediction accounts of ERP N400 modulations in language processing through experimental design. *Neuropsychologia*, *134*, Article 107199. https://doi.org/10.1016/j.neuropsychologia.2019.107199

Masson, M. E. J., & Loftus, G. R. (2003). Using confidence intervals for graphically based data interpretation. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, *57*(3), 203–220. https://doi.org/10.1037/h0087426

Mishra, R. K., Singh, N., Pandey, A., & Huettig, F. (2012). Spoken language-mediated anticipatory eye movements are modulated by reading ability: Evidence from Indian low and high literates. *Journal of Eye Movement Research*, *5*(1), 1–10. https://doi.org/10.16910/jemr.5.1.3

Montag, J. L., & MacDonald, M. C. (2015). Text exposure predicts spoken production of complex sentences in 8- and 12-year-old children and adults. *Journal of Experimental Psychology: General*, *144*(2), 447–468. https://doi.org/10.1037/xge0000054

Ng, S., Payne, B. R., Stine-Morrow, E. A. L., & Federmeier, K. D. (2018). How struggling adult readers use contextual information when comprehending speech: Evidence from event-related potentials. *International Journal of Psychophysiology*, *125*, 1–9. https://doi.org/10.1016/j.ijpsycho.2018.01.013

Nieuwland, M. S., Barr, D. J., Bartolozzi, F., Busch-Moreno, S., Darley, E., Donaldson, D. I., Ferguson, H. J., Fu, X., Heyselaar, E., Huettig, F., Matthew Husband, E., Ito, A., Kazanina, N., Kogan, V., Kohút, Z., Kulakova, E., Mézière, D., Politzer-Ahles, S., Rousselet, G., . . . Von Grebmer Zu Wolfsthurn, S. (2020). Dissociable effects of prediction and integration during language comprehension: Evidence from a large-scale study using brain potentials. *Philosophical Transactions of the Royal Society B*, *375*(1791), Article 20180522. https://doi.org/10.1098/rstb.2018.0522

Nieuwland, M. S., Politzer-Ahles, S., Heyselaar, E., Segaert, K., Darley, E., Kazanina, N., Von Grebmer Zu Wolfsthurn, S., Bartolozzi, F., Kogan, V., Ito, A., Mézière, D., Barr, D. J., Rousselet, G. A., Ferguson, H. J., Busch-Moreno, S., Fu, X., Tuomainen, J., Kulakova, E., Husband, E. M., . . . Huettig, F. (2018). Large-scale replication study reveals a limit on probabilistic prediction in language comprehension. *eLife*, *7*, Article e33468. https://doi.org/10.7554/eLife.33468

Norris, D., McQueen, J. M., & Cutler, A. (2016). Prediction, Bayesian inference and feedback in speech recognition. *Language, Cognition and Neuroscience*, *31*(1), 4–18. https://doi.org/10.1080/23273798.2015.1081703

Novick, J. M., Hussey, E., Teubner-Rhodes, S., Harbison, J. I., & Bunting, M. F. (2014). Clearing the garden-path: Improving sentence processing through cognitive control training. *Language, Cognition and Neuroscience*, *29*(2), 186–217. https://doi.org/10.1080/01690965.2012.758297

Olivers, C. N. L., Huettig, F., Singh, J. P., & Mishra, R. K. (2014). The influence of literacy on visual search. *Visual Cognition*, *22*(1), 74–101. https://doi.org/10.1080/13506285.2013.875498

Pickering, M. J., & Gambi, C. (2018). Predicting while comprehending language: A theory and review. *Psychological Bulletin*, *144*(10), 1002–1044. https://doi.org/10.1037/bul0000158

Pickering, M. J., & Garrod, S. (2013). An integrated theory of language production and comprehension. *Behavioral and Brain Sciences*, *36*(4), 329–347. https://doi.org/10.1017/S0140525X12001495

R Core Team. (2019). R: A language and environment for statistical computing (Version 3.6) [Computer software]. R Foundation for Statistical Computing. https://www.R-project.org/

Roland, D., Dick, F., & Elman, J. L. (2007). Frequency of basic English grammatical structures: A corpus analysis. *Journal of Memory and Language*, *57*(3), 348–379. https://doi.org/10.1016/j.jml.2007.03.002

Rommers, J., Meyer, A. S., & Huettig, F. (2015). Verbal and nonverbal predictors of language-mediated anticipatory eye movements. *Attention, Perception & Psychophysics*, *77*(3), 720–730. https://doi.org/10.3758/s13414-015-0873-x

Saslow, M. G. (1967). Latency for saccadic eye movement. *Journal of the Optical Society of America*, *57*(8), 1030–1033. https://doi.org/10.1364/josa.57.001030

Skeide, M. A., Kumar, U., Mishra, R. K., Tripathi, V. N., Guleria, A., Singh, J. P., Eisner, F., & Huettig, F. (2017). Learning to read alters cortico-subcortical cross-talk in the visual system of illiterates. *Science Advances*, *3*(5), Article e1602612. https://doi.org/10.1126/sciadv.1602612

Smalle, E. H. M., Szmalec, A., Bogaerts, L., Page M. P. A., Narang, V., Misra, D., Araújo, S., Lohagun, N., Khan, O., Singh, A., Mishra, R. K., & Huettig, F. (2019). Literacy improves short-term serial recall of spoken verbal but not visuospatial items—Evidence from illiterate and literate adults. *Cognition*, *185*, 144–150. https://doi.org/10.1016/j.cognition.2019.01.012

Stanovich, K. E., & West, R. F. (1989). Exposure to print and orthographic processing. *Reading Research Quarterly*, *24*(4), 402–433. https://doi.org/10.2307/747605

Staub, A., Clifton, C., Jr. (2006). Syntactic prediction in language comprehension: Evidence from either . . . or. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(2), 425–436. https://doi.org/10.1037/0278-7393.32.2.425

Street, J. A., & Daôbrowska, E. (2010). More individual differences in language attainment: How much do adult native speakers of English know about passives and quantifiers? *Lingua*, *120*(8), 2080–2094. https://doi.org/10.1016/j.lingua.2010.01.004

Van Petten, C., & Luka, B. J. (2012). Prediction during language comprehension: Benefits, costs, and ERP components. *International Journal of Psychophysiology*, *83*(2), 176–190. https://doi.org/10.1016/j.ijpsycho.2011.09.015

Received June 10, 2020
Revision received December 17, 2020
Accepted December 28, 2020 ■