

Literacy can enhance syntactic prediction in spoken language processing

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Abstract

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

Prediction has become the dominant theoretical framework for understanding the functioning of the mind and brain. As well as playing an integral role in perception, action, and learning (Clark, 2013; Friston, 2005), the pre-activation of predictable information is argued to reduce processing load and increase efficiency across multiple cognitive systems (e.g., Bar, 2003). Notably, psycholinguistic research increasingly emphasises the importance of anticipatory mechanisms in language processing (e.g., Altmann & Mirkovic, 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 pre-activation 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) asked a community sample of adults with varying literacy levels to listen to spoken sentences. Proficient readers showed a reduced ERP negativity for strongly predictable target words over anterior channels, in a time window from 170 to 300ms 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 (non-predictive) accounts, such as differences in the integration of non-predicted 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 (Street and Dąbrowska, 2010; Langlois & Arnold, 2020) and production (Montag & MacDonald, 2015), in children and adults (e.g., Crain-Thoreson & Dale, 1992; Dąbrowska, 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 (1) in conjunction with visual displays such as Figure 1.

(1) Het raam wordt inderdaad gebroken door een stier.

The window is indeed broken by a bull.

The auxiliary “wordt” is an early but unreliable indicator of passive voice, since 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 (mean age = 25.2; 25 females). 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, under review). We performed a pre-registered 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. While 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 (Kamide et al., 2003; Arai & Keller, 2013). One participant was excluded because the eye tracker failed to calibrate to their eyes. There is a pronounced group difference in literacy experience, based on Literacy PC1 ($t = 8.70, p < 0.001$). The small difference in non-verbal IQ (Raven's) scores between high and low literacy experience groups ($t = 2.10, p = 0.04$) 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 ($t = 1.79, p = 0.09$). As Literacy PC1 was measured 18-24 months prior to the current study, we re-administered the Author Recognition Test (ART; 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. ART scores remained significantly higher in the HLE group ($t = 4.01, p < 0.001$).

Literacy experience	n	Age	Literacy PC1 score	Non-verbal 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)

Table 1. Descriptive summary of high and low literacy experience groups. Group means are based on raw scores for individual difference measures (except Literacy PC1, a derived score). Standard deviations are shown in brackets. PC1 = First Principal Component; WM = Working Memory. Non-

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

verbal IQ and verbal working memory were assessed using Raven’s Progressive Matrices and the Backward Digit Span task respectively.

Materials

24 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 favour of less typical combinations (e.g., paintbrush-dog).² All experimental sentences used the present-tense passive frame shown in (1), i.e., 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 colour pictures from the MultiPic database (Duñabeitia et al., 2017): an inanimate entity (the patient), an animate entity (the agent, henceforth the target), and two semantically unrelated distractors (Figure 1).

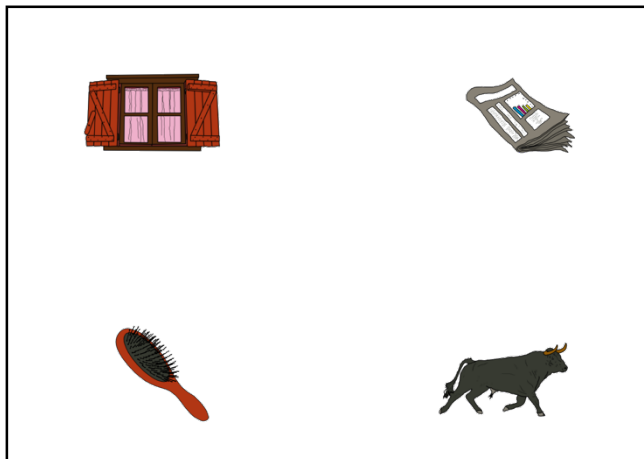


Figure 1. Example visual display for the (passive) spoken sentence “Het raam wordt inderdaad gebroken door een stier” *The window is indeed broken by a bull*, in which “stier” is the target picture. Distractors were always inanimate objects and none were plausible agents of the events described.

² The semantic relatedness of patients and agents (indexed as cosine distance) was similar to that of patients and distractors ($F = 1.15, p = 0.32$). Cosine distances between verbs and targets versus verbs and distractors also did not differ significantly ($F = 1.16, p = 0.32$). The full set of visual stimuli for passive trials is reported in the online supplementary materials.

There were no statistical differences in mean frequency of picture labels (Table 2) in the four sets of pictures ($F = 0.09$; $p = 0.97$). Picture positions were pseudo-randomised 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.

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

Table 2. Descriptive summary of Log10 word frequency values for experimental picture labels, grouped by set (SUBTLEX-NL; Keuleers, Brysbaert, & New, 2010).

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 (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 44kHz (mono) with 16bit sampling resolution.

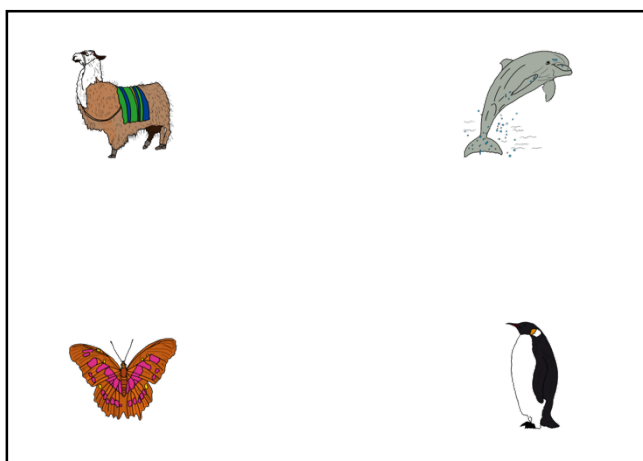


Figure 2. Example filler visual display for the spoken sentence “De vlinder lijkt inderdaad veel kleiner dan een dolfijn” *The butterfly indeed seems much smaller than a dolphin*, in which the unpredictable target word is “dolfijn”.

Procedure

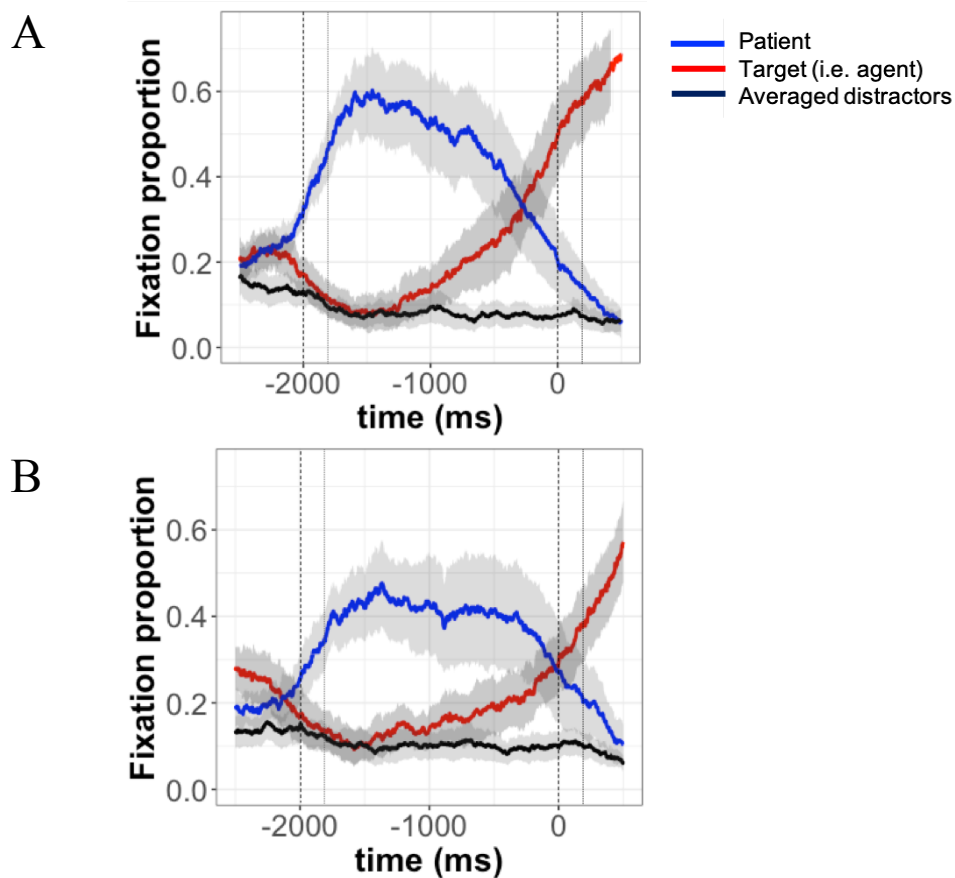
Participants were tested individually in a soundproofed experiment booth. An SR Research EyeLink 1000 tower-mounted eye tracker was used to record eye movements. Participants were instructed to avoid moving their eyes away from the screen and to listen carefully to the sentences presented via headphones (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 one-second central fixation, followed by a visual display. There was a two-second preview of the pictures before the onset of the cue (“wordt”) in the speech signal. The pictures remained on the screen until 2500ms after the onset of the target word. The mean duration of the critical window between cue and target onset was 2005ms in passive trials and 2162ms 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 pseudo-randomised for each participant (with a maximum of two consecutive passive trials). The experiment took approximately 20 minutes, including calibration.

Results

Eyelink DataViewer was used to code fixations, saccades and blinks. Data from four out of 888 experimental trials were missing due to track loss. Fixation locations were coded automatically with respect to pre-defined regions of the visual display: patient, target, distractor 1, distractor 2, and background (i.e., none of the pictures). In the high literacy experience (henceforth HLE) group, 2% of fixations on experimental trials were coded as background. One participant in the low literacy experience (henceforth LLE) group was

excluded due to 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), and a difference score, i.e., 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).



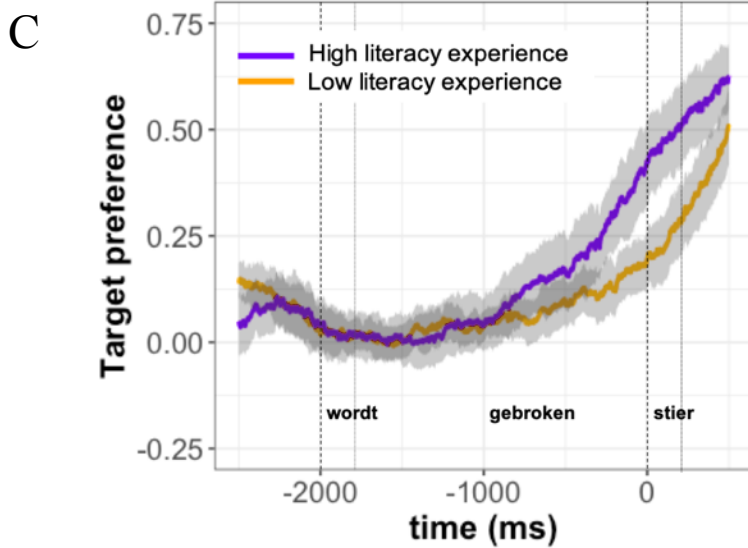


Figure 3. The time window of interest extended from the acoustic onset of “wordt” to the onset of the target word (time zero), both adjusted by 200ms to account for the time taken to program and launch a language-mediated saccadic eye-movement (Saslow, 1967). Panel A plots fixation proportions to patient, target and averaged distractor entities for the HLE group (n=19). Panel B plots fixation proportions to the same entities for the LLE 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, while values greater than zero reflect relatively more fixations to the target. The grey shaded areas represent by-participant 95% confidence intervals, computed at each 1ms sampling step (Masson & Loftus, 2003). Vertical dashed lines indicate the acoustic onsets of “wordt” (mean = -2005) and the target word (time zero). Vertical dotted lines represent a +200ms 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 (mean = -1003ms) is indicated by “gebroken”.

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)

Table 3. Mean fixation proportions (passive trials) to the target, averaged distractors, and the mean difference between them (target fixations minus averaged distractor fixations), as well as mean fixation proportions to the background for the high (HLE) and low (LLE) literacy experience groups during the critical time window (200ms after “wordt” onset until 200ms after target onset). Standard deviations are provided in brackets.

The 14 non-predictive reference items were analysed to provide a baseline for lexical processing speed. This was indexed as the log odds of fixating the target entity in the first 500ms after target word onset (with 200ms 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.

Inferential statistics

To analyse the amount of variance in anticipatory eye movements that could be explained by literacy experience, we fit a linear mixed-effects model (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 (+200ms). We first aggregated gaze durations by participant, item, and display region, 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 (Low/High) was a fixed factor in the model, with Low treated as the reference level.³ The model contained lexical processing speed (calculated as described above and mean centred), 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 non-verbal IQ and verbal working memory scores (mean centred). 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 Supplementary Materials).

³ Descriptive model comparison indicated a better fit for the model with literacy experience as a categorical (AIC = 4694.1) versus continuous predictor (AIC = 4698.3).

There was no robust evidence for an interaction between literacy experience and lexical processing speed, nor for a main effect of lexical processing speed on target preference.

Finally, the results indicate that non-verbal IQ and verbal working memory contributed little to anticipatory eye movements.

Predictor	Coefficient	SE	<i>t</i> 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
Non-verbal 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 x Lexical processing speed	0.53	0.90	0.59	-1.22, 2.29

Table 4. Summary of fixed effects in liner mixed-effects model (N = 837). 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, non-verbal IQ, and verbal working memory. SE = Standard Error; CI = Confidence Interval. 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.

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

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 analysed existing behavioural data from 112 adult native

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, since 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 no evidence 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.,

Dutch speakers (aged 18-35 and diverse in terms of education and ability) who took part in a different study at MPI Nijmegen. This study administered a large battery of individual difference measures, including the Author Recognition Test (ART), and an auditory sentence-picture matching task that assessed comprehension of (amongst 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 ART scores in the bottom quartile (i.e., comparable to 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 non-reversible passives we used (e.g., *De watermeloen wordt inderdaad geschopt door een ezel*, *The watermelon is indeed kicked by a donkey*).

2014; Skeide et al., 2017). Moreover, the minimal contribution of non-verbal 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).

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-Thoresen 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 (e.g., 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, since 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 F. 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 up-coming *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 by-product 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’).

Author note

There has been no prior dissemination of the specific idea or data that appear in this manuscript.

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