The Effects of Prediction and Speech Rate on Lexical Processing

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Abstract

Listeners may predict aspects of upcoming linguistic input before it is encountered, but the specificity of information predicted can vary. It is unclear how very specific lexical predictions influence language processing, and what cognitive processes are involved with this prediction process. The goal of this study was to investigate the effect of specific lexical prediction on language processing, and how this effect varies with speech rate and individual differences in processing speed and working memory. In an active prediction paradigm, participants heard two-sentence passages at fast, medium, or slow rates while predicting the final word of the second sentence. Instead of the final word, participants were instructed to read a word aloud as quickly as possible, then indicate if this was the word they predicted. This word had about a 50% chance of matching the participant's prediction. Both correct and incorrect prediction facilitated reading time as compared with no prediction, suggesting that prediction can facilitate language processing, regardless of prediction accuracy. Additionally, slower speech rate resulted in slower reading time across prediction conditions, indicating that speed of prediction may slow to match speech rate. The effects of prediction accuracy and speech rate were not related to individual difference measures of either processing speed or working memory. In all, these results support the hypothesis that active prediction decreases language processing time, which may also be affected by speech rate.

Introduction

A remarkable aspect of human cognition is the tendency to anticipate or predict future events based on context and memories of previous experiences (Martin, Branzi, & Bar, 2018). Prediction is found in a variety of domains, from basic sensory processing to more complex areas such as social cognition, and can facilitate understanding of complex situations (Bubic, Von Cramon, & Schubotz, 2010). One complex cognitive domain where prediction seems to play an important role is in language comprehension, where prediction can be defined as pre-activation of the semantic and lexical features of linguistic input before it is encountered. The listener does this by using previous knowledge and context to constrain the possible outcomes of the sentence. According to one model, the listener considers multiple predictions simultaneously, and continually checks and updates their hypotheses about the sentence as it unfolds (Kuperberg & Jaeger, 2016). The pre-activated material varies with the listener's arousal, preparedness, or motivation (Ferreira & Chantavarin, 2018; Hintz, Meyer, & Huettig, 2017).

Although predicting upcoming information might seem to impose an extra, unnecessary cognitive demand on language processing, it might in fact be useful for several reasons. First, successful predictions likely make it easier to process that new information, thereby reducing the processing demand when that information is encountered and correspondingly leading to better comprehension (Freed & Cain, 2017; Kuperberg & Jaeger, 2016). Second, prediction might be useful for replacing missing information when not all of the information is available or deciding whether to follow through with an action before it is complete, by predicting what the consequence will be (Caligiore, Tria, & Parisi, 2006). One way that predictions in language might work is by recruiting the language production system, which could be used to facilitate language comprehension (Hintz, Meyer, & Huettig, 2016; Martin et al., 2018).

Evidence for Prediction

Prediction accounts of language processing are often contrasted with integration accounts, which rely on the ability to link new information with old information during language comprehension. Listeners must integrate the meaning of each incoming word with the meaning of the unfolding sentence, the broader sentence context, and their world knowledge, in order to interpret it as a whole (Hagoort, Hald, Bastiaansen, & Petersson, 2004; Van Berkum, Hagoort, & Brown, 1999). This is distinct from prediction, which requires pre-activation of certain aspects of a word before it is encountered in context. Prediction and integration have been operationalized in electrophysiological studies through an event-related potential (ERP) effect known as the N400 (Kutas & Hillyard, 1980). The amplitude of this negative ERP component that occurs approximately 400ms after the onset of a target stimulus may reflect difficulty processing word meaning (Kutas & Hillyard, 1980). The size and latency of this component are presumed to reflect aspects of the word's ability to be easily integrated in a sentence context, but also reflect the word's contextual predictability (Kutas & Hillyard, 1980). Specifically, the size of its amplitude is closely related to a target word's predictability in sentences (Delong, Urbach, & Kutas, 2005). Prediction and integration may work together in that prediction prepares a listener to integrate certain types of new information with old information (Ferreira & Chantavarin, 2018). This is supported by ERP evidence which suggests that prediction reflects pre-activation of linguistic information, which can be seen early in a sentence, and integration reflects plausibility of sentence outcomes, which is considered later, and is used more in less predictable sentences (Nieuwland et al., 2019).

Evidence from electrophysiological and behavioral studies suggest that the amount of information predicted by a listener varies from specific lexical predictions to no prediction at all, depending on the sentence context and the listener. Evidence for prediction during language processing is apparent through pre-activation of semantic, syntactic, or lexical attributes of a word before it is encountered. For example, listeners use both semantic constraints from a verb (*eat*) as well as the form of the verb (*will eat* vs. *will be eaten by*) to predict the final noun phrase, which leads them to make anticipatory eye movements toward a target object (Kamide, Scheepers, & Altmann, 2003). ERP studies also show that listeners pre-activate both syntactic and semantic features of a target noun (Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005; Wicha, Moreno, & Kutas, 2004). Evidence for prediction of specific lexical items as opposed to general concepts or categories includes studies that suggest people not only predict content words, but also specific function words. For example, a magnetoencephalography (MEG) study showed that listeners pre-activate visual attributes of a predicted word when reading (Dikker et al., 2010). Similarly, another study use sentences such as “The day was breezy so the boy went outside to fly…” to show that readers elicit different patterns of responses to not only the noun (kite vs. airplane), but also the preceding articles (a vs. an), indicating that readers pre-activate specific words (Delong et al., 2005). However, a large-scale replication of this study failed to replicate effects of the article expectation, and only showed effects of expectation for the noun (Nieuwland et al., 2018). Similarly, Nicenboim, Vasishth, & Rösler (2020) argue that only semantic features are preactivated, and words with higher cloze probability have a larger number of semantic features that are preactivated by the context. Therefore, words themselves may not be preactivated, but only semantic or grammatical features of the upcoming noun.

Specificity of Prediction

The variation in the type and amount of information predicted suggests that listeners' predictions range from no prior activation (processing only influenced by ease of integration) to specific lexical prediction. While one might expect that listeners predict to the maximum extent and specificity given the information provided and resources available, evidence suggests that, in fact, listeners do not always predict, even when they have the resources available to do so (Wlotko & Federmeier, 2016). Huettig & Mani (2016) even argue that prediction is not necessary for language comprehension. This begs the question: if prediction does not always occur to its maximum extent, is prediction truly beneficial for language processing? While most studies concentrate on what aspects of linguistic information listeners predict, few studies have addressed this question; namely, what is the effect or benefit of prediction on language processing.

There are several reasons why previous studies have failed to address this question. The current methods used to measure prediction during language typically measure predictability of a word in a given context based on the proportion of people who, when asked to complete the sentence, select that word. This value is known as the word's cloze probability (Taylor, 1953). Many studies use high cloze probability sentences (e.g., in the sentence, "she went to the bakery for a loaf of…" the cloze probability for the word "bread" is 0.98), and more studies with low cloze probability are needed to determine if prediction is actually necessary for language comprehension (Block & Baldwin, 2010; Huettig & Mani, 2016). Additionally, the cloze probability only provides an estimation of, on average, whether listeners will consider a given word as a potential outcome in a sentence context. It does not indicate whether a specific individual actually predicted or considered that word in that particular instance. Specifically, individual differences in linguistic experiences can lead individuals to predict different words in the same context. It is important to consider a specific individuals' predictions and how they affect processing because this difference in prediction is related to response times to target words (Verhagen, Mos, Bakis, & Schilperoord, 2018). Graded responses to words of varying cloze probability therefore may not necessarily reflect differences in individual prediction, especially in sentences that are less predictable.

One way to address both the concerns about individual differences as well as the utility and effects of prediction on language processing is to rely on an *active* prediction paradigm, in which listeners are explicitly instructed to predict and then report what they predicted. A study by Brothers, Swaab, & Traxler (2015) used an active prediction paradigm during reading comprehension to distinguish the effects of lexical prediction form semantic plausibility in language comprehension. In each sentence, the cloze probability for the target word was about 0.5 (e.g. in the sentence Thomas didn't like the temperature of his drink. He thought it was much too…" the target word is "hot" is equally likely to be predicted as the word "cold"). Participants were asked to actively predict the target word while reading each passage, then verify whether they correctly predicted the target word. This paradigm isolated prediction from other forms of facilitation such as plausibility, because the target word and the second most probable sentence completion (in this example, "hot" and "cold") were equally plausible and were equally well integrated with the context. This paradigm also allows assessment of individual variation in prediction by asking the participant *what* they predicted instead of assuming participants all predicted the most common option (i.e. the one with the highest cloze probability). Brothers et al. (2015) found that participants' N400 amplitude was decreased in these medium-cloze sentences compared with sentences ending in an improbable target word, suggesting that semantic plausibility facilitates processing regardless of prediction accuracy. However, in the medium-cloze sentences, trials where participants correctly predicted the target word (in the example above*, hot*) resulted in an N400 with an earlier onset and decreased amplitude compared with trials where participants made the reasonable but incorrect prediction (*cold*) in the same sentences. This suggests that correct lexical prediction facilitates earlier lexical processing beyond the effects of semantic facilitation. Since this study used active prediction, this does not determine whether prediction always occurs during listening comprehension. However, this work does provide support for the idea that when prediction does occur, it can facilitate the processing of the predicted words and also, to a lesser extent, words that are semantically related to the predicted word (Brothers, Swaab, & Traxler, 2015).

Other factors impacting predictive language processing

Speech Rate

When looking at effects of prediction on language processing at the individual level, it is essential to consider aspects of language context that may impact the utility of prediction, beyond the sentence itself. Previous research shows that, regardless of their ability to predict in a certain linguistic context, whether or not people use prediction as a strategy depends on speech rate (Huettig & Guerra, 2019; Wlotko & Federmeier, 2016). Using EEG measurements, when two-sentence passages were presented at slow or fast rates, pre-activation of information was less common at the fast rate (Wlotko & Federmeier, 2016). This suggests that, with increased rate of presentation, participants switched to a different comprehension technique that does not involve top-down prediction. This was interpreted as less time to predict or fewer resources being available to allocate to prediction when the input is faster. However, the same study showed that participants did still predict in the fast condition if they were shown the slow condition first, but not if they experienced the fast rate condition first, suggesting that the conversion to a different comprehension technique is not a result of an inability to predict (Wlotko & Federmeier, 2016). In an experiment measuring eye-tracking in the visual world paradigm, older participants were less quick to look to and click on the correct object when speech rate was faster (Koch & Janse, 2016). A similar study found that participants always predicted the final object during slow speech, but only predicted it during normal speech if they viewed the reference images for a longer period of time before the start of the sentence (Huettig & Guerra, 2019). These studies indicate that speech rate affects the use of prediction in language processing, suggesting that the effect of prediction on language processing may be different at different speech rates.

Working Memory and Processing Speed

The effect of prediction at different accuracies and speech rates may also depend on general cognitive processes used in language processing. Two general cognitive processes that may be related to predictive language processing are working memory and processing speed. Using Dutch gender-markings of pronouns to facilitate prediction of nouns, one study found that working memory and processing speed independently affected anticipatory looks to a target noun object (Huettig & Janse, 2016). Another study using the same paradigm found that participants were faster to look at a target object in predictable sentences, and this was inhibited by imposing a memory load on participants while performing the task (Ito, Corley, & Pickering, 2018). This shows that predictive language processing relies on more general cognitive resources, which are limited in capacity. Additionally, processing speed can interact with working memory in that when sentences that required more processing time, working memory limited comprehension abilities. Working memory may be used for construction of sentence meaning and comprehension, whereas processing speed may be required for syntactic construction (Waters & Caplan, 2005). Furthermore, speech rate may interact with individual working memory or processing speed to affect prediction. Faster speech rates may affect the recognition of spoken language by increasing the amount of information to process, and reducing clear articulation (Koch & Janse, 2016). In terms of working memory, slow speech may facilitate language processing at high working memory, but hindered processing at low working memory (Small, Andersen, & Kempler, 1997).

In sum, previous studies show that prediction, or pre-activation of language information on multiple levels is possible and can be beneficial, but it does not always occur. Speech rate may affect the use of prediction in language processing. Other differences in effects may be related to individual differences in working memory or processing speed. While previous research focuses on whether and to what extent prediction can occur in linguistic situations, few studies have measured the potential cost and benefit of active prediction during language processing. The active prediction paradigm by Brothers et al. (2015) uses medium-cloze probability sentences to measures the effect of lexical prediction on sentence processing. This can help determine why prediction may or may not be used by different individuals in different contexts based on how prediction facilitates or hinders language processing when listening to speech at different rates.

Current Study

The goal of the current experiment was twofold: first, to investigate the effects of lexical prediction by using an active prediction paradigm (cf. Brothers et al., 2015) and, second, to investigate how lexical prediction is influenced by speech rate and relates to individual differences in working memory and processing speed. If lexical prediction involves pre-activation of a specific lexical item at the exclusion of other items, it should be advantageous when that prediction is accurate, but not helpful (and potentially lead to interference) when incoming information does not match the predicted/pre-activated lexical item. In contrast, if lexical prediction involves pre-activation a specific lexical item, but extends activation to other items in a similar sematic field, then it should be advantageous whether that prediction is accurate or not. In either case, if prediction is useful for language processing, both correct and incorrect prediction should be advantageous compared with no prediction at all. Slower speech rate may facilitate stronger predictions by allowing more time for prediction and accelerate language processing. Alternatively, faster speech rate may instead accelerate language processing by promoting faster prediction. Finally measures of individual differences in processing speed and working memory are expected to modulate the effects of prediction accuracy and speech rate on response time.

Method

The design and analysis plans were preregistered on the Open Science Framework – https://osf.io/5gpwc – and were conducted as proposed except as noted below.

Participants

The participants for the study were 42 students at the University of Maryland. All were native English speakers and over the age of 16. Unfortunately, research restrictions resulting from the COVID-19 pandemic made it impossible to reach the target preregistered N of 80 participants.

Stimuli and Procedure

Lexical Prediction Task

The stimuli for the lexical prediction task were adapted from Brothers et al. (2015), and consisted of 180 critical words appearing at the end of two-sentence passages. The cloze probability range for the passages is 40% to 60%. The sentences are designed so that each sentence has two likely final words, each with a cloze probability of about 50% – see Table 1 for example stimuli. The passages, minus the final word, were recorded via Text to Speech Converter for Windows 10 at standard speed, then *fast* and *slow* versions were created in Audacity (version 2.3.2) by using high-quality tempo chance to change the speed of the audio files without changing pitch. Fast versions were changed by 50% to be 67% of the original duration, and slow versions were changed by -60%, to be 250% of the original duration. Stimuli were arranged into three counterbalanced lists such that all participants listened to each passage once, either at a slow, medium, or fast speech rate, and each passage occurred at each speech rate across participants. The order of the passages was randomized for each participant. Sentences were read through headphones at a fast, medium, or slow rates. All participants heard 1/3 of the sentences at each rate.

Table 1: Example passages used in the experiment[1]

Passage Audio	Target Word
The author is writing another chapter about the fictional detective. To date, he thinks it will be his most popular…	Novel
Grandma Tootsie was walking on the icy sidewalk. Her grandson supported her arm so she would not …	Slip
The old school teacher wanted to draw the diagram up on the board. Unfortunately, he could not find his …	Chalk
John had been working all day and flopped down on the bed. He definitely needed to get some …	Rest
The carpenter climbed up a ladder to repair the house. A recent wind storm had blown off the …	Roof
Dan walked past the playground during recess. He heard the laughter of all the cute little …	Children
Hilda was interested in politics. She hoped one day to become the mayor of her …	City

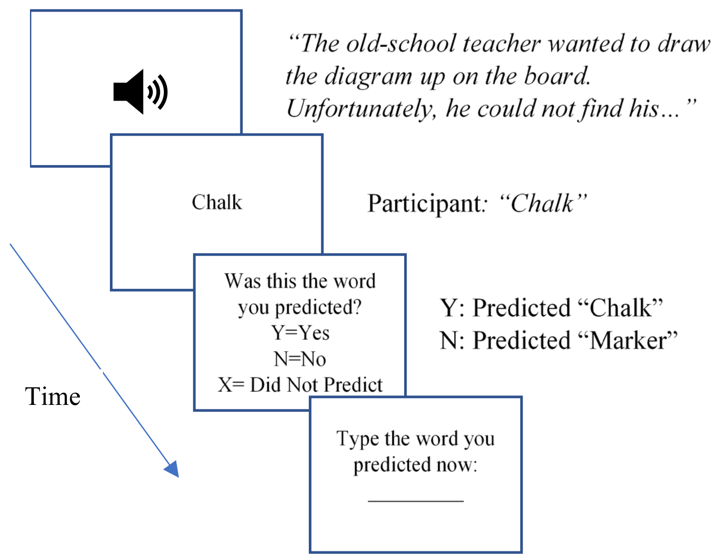
[1] We would like to thank Trevor Brothers for sharing the stimuli for the experiment

Tim wouldn't eat any kind of seafood with claws. He especially didn't like …	Crab
Near the intersection, Bill was texting. He did not notice that the light had turned …	Red
David has to pick between the two alternatives before Monday. He doesn't think he'll be able to …	Decide
To test them, Steve smelled the clothes in the laundry basket. He realized that they were all …	Dirty

An overview of the experimental paradigm is shown in Figure 1. Participants were instructed to actively predict the final word of the second sentence while listening to each passage. On critical trials, the final word for each passage was omitted from the sound file but appeared on the screen 250ms after the offset of the penultimate word. The participant was instructed to read this word aloud into a microphone as soon as possible, which recorded the word that they said and the timing of voice onset. Participants were then asked whether they were predicting the word that appeared on the screen, a different word, or no word at all. If they predicted a different word, they were asked to type the word they predicted. Additionally, to ensure that participants were listening to the sentences and actively predicting during the sentence, a subset of the sentences (35 sentences) ended with a blank line appearing on the screen instead of a word, and participants were instructed to instead say their predicted word aloud as fast as possible[2].

[2] Although the task was initially administered using PsychoPy (v. 3.1.5), data collection moved to use PsyScope X (Build 77) after the first 10 participants due to technical problems.

Figure 1: The experimental paradigm



Individual Differences Measures

Following the lexical prediction task, participants took standard laboratory assessments of working memory and processing speed (two measures of each construct). All of these measures were from the Psychology Experiment Building Language (PEBL) test battery (Mueller & Piper, 2012).

Working Memory*:* Two tasks for verbal working memory measured the ability to store and manipulate verbal information as this is important for sentence processing (Caplan & Waters, 1999). The *digit span backward* and *operation span* measures from the PEBL test battery were used because they are commonly-used verbal working memory tasks that do not involve language processing (Baddeley & Hitch, 2013). In the backward digit span, participants were asked to repeat a series of digits in reverse order right after it is presented. The starting length was three digits, and there were two trials of each length, presented in increasing order up to ten digits. The task ended when two trials of a given length are answered incorrectly or when the trials with ten digits is complete. The task was scored as the number of trials answered correctly and the maximum number of digits recalled. The operation span task consisted of a storage task that required remembering letters and a distractor task that required performing mathematical operations. This is a complex span task that requires simultaneous cognitive processing and storage of the information in memory. This measure is correlated with reading and counting spans, but does not require language, and therefore is not affected by language abilities (Conway et al., 2005; Daneman & Merikle, 1996). The task consisted of 17 trials. On each trial, participants alternated between answering a math operation and seeing a letter. Participants first practiced each task separately. For the distractor task, an equation (e.g. 6 + 2 – 3) would appear on the screen. Participants were instructed to click the mouse when they know the answer. Next, a number appeared on the screen, along with the words *true* and *false*. Participants were instructed to answer correctly as quickly as possible. Finally, a letter would appear on the screen for 1000ms. At the end of the trial, the participant would recall all of the letters they had seen. The number of letters was random and ranged from 2 to 7. The task was scored as the number of trials answered correctly and the maximum number of letters recalled.

Processing Speed: The processing speed measures were the *letter-digit substitution* and the *visual search* tasks from the PEBL test battery. The letter-digit substitution task involves using a key to match the number to its corresponding letter. Participants were instructed to type the number that corresponds to a letter as quickly as possible. The task consisted of 40 trials. On each trial, a different letter would appear in the center of the screen. For the duration of the task, a key was present at the top of the page, which consisted of the number 1-9 and nine corresponding letters. Participants were instructed to type the number that corresponds with the letter in the center of the screen as quickly as possible. This task does imposes minimal demands on other cognitive abilities such as working memory or inhibitory control, has been related to other measures of processing speed, and includes both motor and perceptual speed (Kochari, 2015; Salthouse, 1996). Several other studies have used this measure to measure processing speed in studies of predictive language processing (Huettig & Janse, 2016; Koch & Janse, 2016; Kochari, 2015; Waters & Caplan, 2005). This task was scored as the average reaction time to each letter. A visual search task was used as an additional measure of processing speed; this task involves quickly searching a screen for the letter X or O among an array of other letters. There were 180 trials of this task. On each trial, the letter X or O would appear in the center of the screen to indicate the search target. Next, an array of letters would appear on the screen. Participants were instructed to search for the target letter and click the mouse when they found the target or determined that it was not present. Finally, the same array would appear, only with circles instead of letters. The participant was instructed to click the circle in the place of the target letter, or click "none." This task measures visual processing speed and is related to other measures of general processing speed (Hättenschwiler, Merks, Sterchi, & Schwaninger, 2019; Owsley, 2013). This task was scored as the average reaction time to the first mouse-click, indicating the time to locate the target letter.

Results

Analysis

The effects of prediction accuracy and speech rate on naming times were analyzed in linear mixed effects models using the lme4 package (version 1.1.21; Bates, Maechler, Bolker, & Walker, 2015) in the statistical software R (version 3.6.1; R Core Team, 2019) according to the preregistered plan: https://osf.io/5gpwc. Fixed effects were included for prediction accuracy and speech rate, and random effects were included for participants and items. Because models that included the full random effects structure did not converge, the random effects structure for each was simplified as necessary, following the criteria described in Slevc, Davey, and Linck (2016). The final converging models are reported in Tables 2 & 3.

Participants were excluded according to the pre-registered plan. The criteria for exclusion were if they selected “no prediction” on more than 75% of trials, did not produce an appropriate filler word on more than 50% of trials, or took longer than three seconds to make a prediction on filler trials. These participants were excluded because the study requires that they are making predictions while listening to the passage (prior to the appearance of the target word), and if they are not making predictions immediately and accurately then they may not be predicting during the passage. Although criteria for the exclusion of individual trials was not preregistered, trials in which participants did not speak the target word, spoke a word that was not the target word, or make a noise before speaking the target word were excluded. These were excluded because the dependent variable is the response time to speak the target word, and this cannot be measured if the response time does not reflect the speaking of the target word. For one participant, every “incorrect” and “no prediction” trial was excluded based on these criteria. Data from this participant were therefore excluded entirely, although this was not part of the preregistered exclusion criteria for a participant. Note, however, that including this participant’s data does not notably change the pattern of results described below.

The effect of prediction accuracy (correct, incorrect, or no prediction) was analyzed using three level effects of prediction accuracy, dummy coded with “no prediction” as the reference level. The effect of speech rate (slow, medium, or fast), coded using linear and quadratic orthogonal contrasts, and prediction accuracy was analyzed including only trials in which participants responded “correct” and “incorrect”, according to the preregistered plan.

Table 2 shows the percentages of trials of each prediction accuracy, as indicated by the participants, separated by fast, medium, and slow trials. Participants predicted the target word on 60.4% of trials. They predicted an incorrect word on 30.4% of trials. Participants indicate that they did not predict on 9.2% of trials. Participants' responses were not evenly distributed (χ^2=39.7, p<0.001); instead, participants were most likely to indicate that they predicted the target word and least likely to indicate that they did not predict.

Table 2: Participant reported Prediction Accuracy

	% Prediction Accuracy					
	No Prediction		Incorrect		Correct	
Speed	M	SD	M	SD	M	SD
Fast	10.1 (4.5)	17.7	29.2 (13.1)	14.3	60.7 (27.2)	20.0
Med	9.0 (4.1)	17.2	28.7 (13.0)	15.1	62.3 (28.2)	19.7
Slow	8.6 (3.9)	16.9	33.1 (15.1)	14.6	58.3 (26.6)	18.7
Total	9.2 (12.5)	17.1	30.4 (41.2)	13.8	60.4 (82.0)	18.8

Note: Mean and standard deviation for prediction accuracies (No prediction, Incorrect, and Correct) are reported as percent of trials for each speed. Mean number of trials at each prediction accuracy is reported in parentheses

Effect of Prediction Accuracy

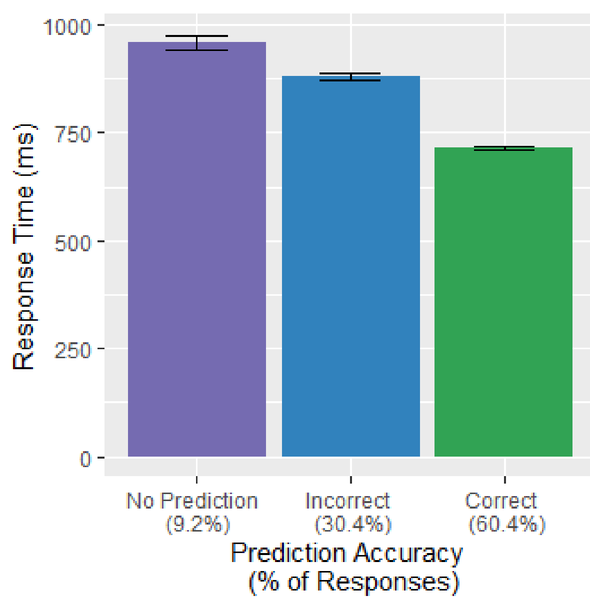
Figure 2 plots the average response time for each type of prediction accuracy and Table 3 reports the statistical results. The fastest response times were for the correct prediction accuracy trials, followed by incorrect prediction accuracy. The slowest response times were for the trials with no prediction. There was an effect of prediction accuracy such that response times for correct prediction and incorrect prediction were less than no prediction, and response times for correct prediction were less than incorrect prediction. These results indicate that correct prediction of the target word was the strongest facilitator response time for the target word, providing support for effects of specific lexical prediction. Incorrect prediction also facilitated processing of the target word, suggesting additional semantic facilitation for prediction of a related word.

Table 3: Mixed effects model examining the effects of prediction accuracy on response time.

				Random Effects			
	Fixed Effects			By Participant			By Item
Parameters	Estimate	SE	t	SD	Prediction 1	Prediction 2	SD
Intercept	6.64	0.03	190.69*	0.22	1.00	0.16	0.61
Prediction Correct vs. No Prediction	0.07	0.01	6.10*	0.61		0.16	
Prediction Corect vs. Incorrect	0.07	0.01	5.22*	0.31			

Note: Prediction accuracy was dummy coded with correct prediction as the reference label. Model formula: lmer(log(ResponseTime)~Prediction+(Prediction|Participant)+(1|Passage)

Figure 2: Effect of Prediction Accuracy on Response Time



Effect of Speech Rate

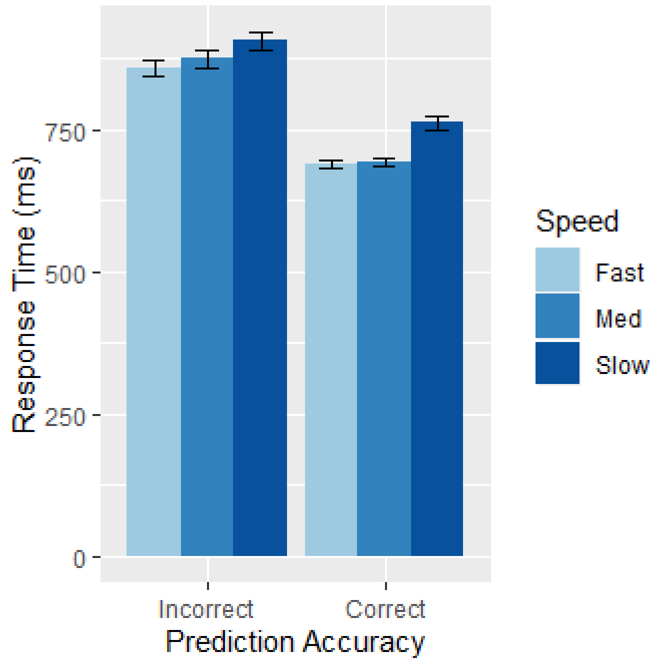
Figure 3 plots the average response times for speech rate and prediction accuracy and the statistical results are reported in Table 4. There was a main effect of speech rates such that response times for slow speech rate were greater than response times for medium and fast speech rates. There was no difference between response times for medium and fast speech rates. There was no interaction between speech rate and prediction accuracy for either fast rate or slow rate. These results suggest that listeners adjust their prediction speed using cues from speech rate so that when speech rate changes, speed of prediction changes as well, and the prediction is used to process linguistic information. This claim is further supported by the fact that there is no effect of speech rate on response time for the trials in which participants did not predict (b=4.48, SE=41.28, $t=0.109$, *n.s.*), suggesting that the faster processing of the target word relies on faster prediction.

Table 4: Mixed effects model examining the effects of prediction accuracy and speech rate on response time.

				Random Effects			
	Fixed Effects			By Participant		By Item	
Parameters	Estimate	SE	t	SD	Prediction	SD	Prediction
Intercept	784.2	28.2	27.8*	173.6	0.5	45.1	-0.04
Prediction	87.1	12.5	7.0*	61.3		27.3	
Speed Slow	53.1	10.1	5.2*				
Speed Fast	-13.4	10.3	-1.3				
Prediction x Speed Slow	-7.8	10.2	-0.8				
Prediction x Speed Fast	-9.0	10.4	-0.9				

Note: Prediction accuracy only included correct prediction and incorrect prediction. Speed was dummy coded with medium speed as the reference label. Model formula:
lmer(ResponseTime~Prediction*Speed+(Prediction|Participant)+(Prediction|Passage))

Figure 3: Effect of Speech Rate and Prediction Accuracy on Response Time



Individual Differences: Exploratory Analyses

Relationships between the effect of prediction accuracy on response times and the effect of speech rate on response time with individual differences in general processing speed and working memory were analyzed in a correlation matrix, which is presented in Appendix A. There were no relationships between prediction accuracy or speech rate effects with measures of general processing speech or working memory. This may reflect the sample size, which is likely too small to observe reliable individual differences. While not modulating any of the effects of prediction accuracy or response time, the measures of processing speed were related to response times (*b*=-77.3*, SE*=29.55 ,*t*= -2.616, *p*=0.013).

Discussion

The specificity of prediction in language processing has been shown to vary across context, with more constraining sentences eliciting more specific predictions. Therefore, it was unclear how highly specific lexical prediction might affect language processing in medium-cloze probability sentences. This study used an active prediction task to investigate the role of specific lexical prediction in language processing, to determine whether it has an effect on language processing that is separate from semantic facilitation. Additionally, this study examined how contextual differences created by various speech rates might affect lexical prediction and its implications for language processing. Active lexical prediction and semantic prediction each facilitated language processing. Furthermore, listeners used contextual information about speech rate to alter their prediction rate such that it can be used to process language.

Effect of Prediction Accuracy

Findings from this study suggest that active prediction best facilitates language processing time when the lexical prediction made by a listener is correct, however, incorrect predictions also facilitate language processing time compared to no prediction. This indicates that specific lexical prediction is advantageous to language processing beyond prediction of more general semantic or syntactic attributes of words. This conclusion follows because, in this experiment, both the incorrect prediction and target word were semantically related and equally plausible in the sentence context (e.g. in “The old school teacher wanted to draw the diagram up on the board. Unfortunately, he could not find his...” the target word “chalk” and the incorrect prediction “marker” are semantically related and equally plausible). Therefore, if listeners could only predict syntactic or sematic features of the target word to facilitate language processing, then correct prediction would have no advantage over incorrect prediction, Instead, correct lexical prediction was especially facilitative, suggesting an effect of lexical prediction. However, lexical prediction was not the only source of faster processing. There was a smaller processing advantage for incorrect predictions compared with no prediction. This suggests that semantic predictions facilitate processing of the target word in addition to lexical prediction.

Given that this study used active prediction, these results cannot show that lexical (or sematic) prediction always occurs during language processing, nor that it is necessary, but that when it does occur, it facilitates the speed of language processing.

Similar conclusions were drawn by Brothers et al. (2015) for active prediction during reading from ERP recordings. Correct prediction accuracy resulted in earlier lexical processing of the target word, and a facilitation effect, demonstrated by a reduction in size of the N400 amplitude. Contextual semantic constraint was also related to a decrease in size of the N400 amplitude, suggesting that semantic prediction also has a facilitation effect. The current study supports these findings in a behavioral paradigm, and extends these findings to auditory lexical prediction.

These findings do not align with arguments that only sematic or syntactic prediction can facilitate language comprehension (Nicenboim, Vasishth, & Rösler, 2020; Nieuwland et al., 2018). These arguments reason that specific lexical prediction is only the target with the most relevant semantic features. The stimuli for this experiment were designed such that two potential target words were equally plausible. Therefore, on incorrect trials, the predicted word and the target word did not differ in the number of relevant semantic features. Another reason for this discrepancy may be the use of active prediction. While lexical prediction facilitates language processing when listeners were explicitly instructed to predict, listeners may not naturally use lexical prediction in medium-predictability sentences. Support for this potential explanation comes from an ERP study suggesting that when the target word is predicted incorrectly but is still semantically congruent in the sentence context, the listener shows lexical inhibition for the predicted word (Ness & Meltzer-asscher, 2017). If the incorrect prediction is lexically inhibited, this could explain why processing of the target word takes longer in these trials. This active inhibition could also explain why listeners do not always make specific lexical predictions during language processing for moderately-predictable sentences. Despite having a processing time advantage over no prediction, incorrect prediction may require effortfully inhibition of the lexical prediction, and therefore only using semantic prediction for moderately-predicable sentences may be preferred.

Effect of Speech Rate

The results of this study also suggest that participants use contextual cues about the speech rate of linguistic input to adjust their speed of lexical prediction and so that it can be used for language processing at the correct time. While only slow speech showed a significant difference from the other rates in response times, this may be because of the specific rates chosen. It is critical to note that the effects of speech rate on response time were not apparent for cases where participants did not make a prediction. This indicates that speech rate modulated the speed of prediction specifically, not just the speed of language processing in general.

These results are consistent with an eye tracking study showing that listeners rapidly use early contextual cues about speech rate to adjust their perception of an ambiguous determiner and use this information to predict a target object (Kaufeld, Naumann, Meyer, Bosker, & Martin, 2019). In German, the determiners *ein* and *eine* only differ by one vowel sound. When the form of the determiner was made ambiguous (the differentiating vowel was short enough that is could not be reliably perceived), participants were more likely to look toward the target that uses the determiner with the longer vowel sound at fast speech rates, thereby using information about speech rate to infer how rate affects the speech signal and to rapidly use this for prediction (Kaufeld et al., 2019).

However, these results are inconsistent with findings from another eye tracking study, which suggests that listeners do not always use prediction during language comprehension, and that the use of prediction depends on the rate of speech (Huettig & Guerra, 2019). Using gender-marked determiners in Dutch to predict a target object, listeners predicted the target during slow speech, indicated by looking to the target object before the onset of the target word. During normal speech, they only predicted if they had a longer preview of the objects or were explicitly instructed to predict, but explicit instruction only led to a small effect of prediction. The current study is different because it involves lexical prediction instead of object prediction in the visual world. It is possible that faster speech allows for linguistic prediction, but not faster linking to a visual scene (Huettig & Guerra, 2019).

Relationship with Cognitive Measures

In this experiment, the effects of prediction and of speech rate on naming times did not correlate with composite individual differences measures of working memory or processing speed. This suggests that these cognitive abilities do not modulate the effects of speech rate or prediction accuracy on language processing time. These findings about processing speed were similar to an eye-tracking study measuring at the effects of natural speech rate variation and fluid cognitive processing (combined processing speed and reasoning) on fixation to a target object in a visual display. In sentences with a wide range of predictability for target objects, slower speech rate and better fluid cognitive processing decreased time to fixation, but fluid cognitive processing did not modulate effects of speech rate (Koch & Janse, 2016).

In contrast, the current findings suggesting prediction is unrelated to both processing speed and working memory differ from other studies of predictive language processing using visual world referents, which suggest that working memory and processing speed each accounted for variance in predictive eye movements (Huettig & Janse, 2016; Huettig, Rommers, & Meyer, 2011). However, these studies argue that working memory is used to link language referents to the visual world, which was not necessary in our study. Also, slower processing speed was related to older age in their sample of participants ranging from ages 35 to 77. To fully untangle the question of whether these general cognitive abilities are related to predictive language processing that does not require accessing visual representations, a larger and more demographically heterogeneous sample would be needed.

Limitations

It is important to consider several limitations of this study. First the active prediction paradigm is likely quite different from natural language processing. Using the same stimuli we used here, Brothers, Swaab, & Traxler (2017) contrasted reading times for target words when participants were and were not explicitly instructed to predict and found that there was a greater effect of prediction accuracy when they were explicitly instructed to predict. This indicates that the effects of specific lexical prediction may not be the same in the absence of active prediction. Therefore, these results can only be interpreted to the extent that the listener is actively predicting during language comprehension.

Similarly, language processing in this study was measured by the time to read and produce the target word, which one may argue reflects the time preparing to produce the target word instead of the time to comprehend it. This contrasts with other behavioral paradigms for predictive language processing, which have measured eye tracking during reading as a measure of comprehension. While it may seem that production latencies reflect ease of production instead of ease of processing, it is important to note that production itself has been suggested to play an important role in the prediction process (Hintz et al., 2016; Martin et al., 2018).

Specifically, when intermixing a production task with a comprehension task, participants increased their use of prediction on the comprehension task, which led to faster processing (Hintz et al., 2016). These findings provide support for this active prediction paradigm when assessing the role of prediction in language processing because production, prediction, and language comprehension are tightly integrated.

Another potential limitation is that the reporting of prediction accuracy, specifically correct incorrect, or no prediction, could only be measured by participant report, and therefore cannot be confirmed for accuracy. However, this paradigm offers insight into individual predictions that cannot be measured by assuming individuals' predictions based on population averages, and allows observation of prediction accuracy in medium-predictability sentences. Although the correct prediction accuracy did not match the cloze ratings of the target words in each sentence, Brothers et al. (2015) found that cloze probability for these stimuli did match probability of correct prediction reported by participants in their active prediction paradigm.

Conclusion

The argument for prediction during language processing varies from specific lexical predictions to more general predictions of semantic features. Instead of asking *what* listeners predict, this study instead asked *how* highly specific lexical predictions influence lexical processing, and how this effect varies with speech rate. This was investigated in medium-predictability sentences, where specific lexical prediction has been studied less frequently. Both lexical prediction and semantic prediction facilitated language processing, and listeners used speech rate to adjust their prediction speed and use it for language processing. However, the effects of prediction were independent of speech rate, and individual differences in working memory and processing speed were unrelated to the effect of prediction. These results support the idea that listeners may use both lexical and semantic prediction, since they both benefit language processing. They also suggest that listeners continue to benefit from both types of prediction even when linguistic context changes due to variation in speech rate.

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Appendix A

Correlations among prediction accuracy, speed, and composite scores for processing speed and working memory

Measure	Processing Speed	Working Memory	Prediction Accuracy	Speed
Processing Speed	--			
Working Memory	-0.2255726	--		
Prediction Accuracy	0.1818025	0.1645834	--	
Speed	-0.0140807	-0.0718555	-0.0807315	--