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ARTICLE

Lexical influences on predictive mouse cursor movements

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Abstract

Two mouse cursor tracking experiments investigated lexical prediction. Participants heard predictive sentences (e.g., "What the librarian will read, which is shown here, is the…") and viewed visual arrays with predictable targets (e.g., book) and phonological competitors (e.g., bull) or unrelated distractors (e.g., goat). Participants tasked with clicking on the (i.e., target) object referred to in sentences (Experiment 1), or with doing so interleaved with a cloze procedure (e.g., completing "What the librarian will read is this."; Experiment 2), made predictive mouse cursor movements to targets. However, predictive attraction to phonological competitors was not observed. Implications for theories of predictive sentence processing are discussed.

Keywords: lexical prediction; mouse cursor tracking; phonological competition; predictive sentence processing

1. Introduction

Lexical prediction refers to the pre-activation of word forms (e.g., reflecting their phonology and/or orthography) before these words are heard or read during sentence processing (e.g., Luke & Christianson, 2016). Lexical prediction has attracted considerable attention (e.g., De Long et al., 2005), but is not without controversy (e.g., Nieuwland et al., 2018). Crucially, how pervasive lexical prediction is and how pervasive its effects are across methodologies remain unresolved. The aim of this study was to assess the pervasiveness of lexical prediction by using mouse cursor tracking to capture comprehenders' predictive behaviours.

Predictive sentence processing is supported by evidence from the visual world paradigm (e.g., Tanenhaus et al., 1995). For example, participants in Altmann and Kamide (1999) heard predictive sentences like 'The boy will eat the…' and viewed visual scenes with predictable targets like a cake and other unrelated distractors. Before hearing the predictable target word (e.g., "cake"), participants predictively fixated the target, suggesting that it was pre-activated. However, these findings do not resolve whether comprehenders pre-activate the forms of words (i.e., throughout, form is used to refer to phonological and/or orthographic representations) or merely their semantics (e.g., edible). Building on these findings, participants in Ito et al. (2018) heard predictive sentences like 'The tourists expected rain when the sun went behind the…' and viewed visual arrays with predictable targets like a cloud, phonological competitors like a clown or unrelated distractors like a globe. Before hearing the predictable target word (e.g., "cloud"), participants predictively fixated the phonological competitor, suggesting that the form (e.g., "kla") of the target word was pre-activated, which co-activated the phonological competitor. Kukona (2020) replicated this finding, and studies in Mandarin (e.g., Li et al., 2022; Li & Qu, 2024; Xu et al., 2024; Zhao et al., 2023) also provide converging evidence. Taken together, these findings suggest that comprehenders generate lexical predictions during sentence processing.

The study of lexical prediction is closely connected to the cloze procedure (e.g., Taylor, 1953). Participants in the cloze procedure are typically tasked with completing (i.e., incomplete) sentence fragments. For example, (i.e., norming) participants in Ito et al. (2018) were tasked with completing sentence fragments like 'In order to have a closer look, the dentist asked the man to open his _', which 100% of participants completed with the word 'mouth'. The cloze probability of 'mouth' was thus 100%, which is calculated as the percentage of participants who provided this completion. Cloze probabilities provide a measure of lexical predictability that is widely used in other tasks (e.g., to confirm the predictability of stimuli). The cloze procedure also provides evidence that comprehenders can activate (e.g., produce) word forms that are predictable given a sentence fragment, which is not unlike lexical prediction, at least when they are explicitly tasked with doing so. Moreover, Pickering and Gambi (2018) hypothesise that comprehenders can generate lexical predictions during sentence processing generally by engaging cognitive processes like they do in the cloze procedure, including production processes (e.g., which are essential for producing word completions in the cloze procedure), which they term prediction-by-production.

Lexical prediction is not without controversy. For example, participants in De Long et al. (2005) read sentences like 'The day was breezy so the boy went outside to fly…', which had a high cloze probability ending like 'a kite' or a low cloze probability ending like 'an airplane' with differing articles. During the article, high versus low cloze probability endings yielded differing ERP responses, suggesting that the form (e.g., consonant versus vowel onset) of the noun was pre-activated. These findings complement Ito et al. (2018) and support theoretical approaches like prediction-by-production (e.g., Pickering & Gambi, 2018), suggesting that comprehenders generate lexical predictions during sentence processing. In contrast, Nieuwland et al. (2018) recruited hundreds of participants across multiple labs and did not replicate this finding from De Long et al. (2005), suggesting that comprehenders may not generate lexical predictions. Clark (2013) hypothesises that prediction is fundamental to cognition, yet these findings suggest that lexical prediction may be surprisingly elusive.

The aim of this study was to capture comprehenders' ability to pre-activate word forms using mouse cursor tracking. To summarise, while lexical prediction is supported by findings from the visual world paradigm (e.g., Ito et al., 2018), evidence from the wider literature is mixed (e.g., Nieuwland et al., 2018). Thus, fundamental questions remain about the pervasiveness and importance of lexical prediction, and further study, applying a diversity of methodologies, is essential for advancing understanding. Across a range of psycholinguistic studies, participants' mouse cursor movements have been found to closely complement their eye movements. For example, participants in Allopenna et al. (1998) heard words like 'beaker' and viewed visual arrays with targets like a beaker, phonological competitors like a beetle and unrelated distractors like a carriage. Shortly after hearing the onset of the word, participants fixated the competitor more than distractor. Complementing this finding, participants in Spivey et al. (2005) heard words like 'candle' and viewed visual arrays with targets like a candle and phonological competitors like a candy or unrelated distractors like a jacket. Participants' mouse cursor movements to targets (i.e., which they were tasked with clicking on) were more attracted to competitors than distractors, which Kukona and Jordan (2023) also replicated using internet-mediated mouse cursor tracking. In addition, predictive sentence processing is supported by evidence from mouse cursor tracking. For example, participants in Kukona (2023; see also Kukona & Hasshim, 2024) heard predictive sentences like 'What the man will ride, which is shown on this page, is the…' and viewed visual arrays with predictable targets like a bike and unrelated distractors like a kite. Before hearing the predictable target word (e.g., "bike"), participants made predictive mouse cursor movements to the target, suggesting that it was pre-activated (e.g., including when hearing rapid speech). These findings complement Altmann and Kamide (1999), but likewise, do not resolve whether comprehenders pre-activate the forms of words or merely their semantics (e.g., rideable).

Building on both Ito et al. (2018) and Kukona (2023), this internet-mediated study assessed (i.e., predictive) phonological competition using mouse cursor tracking. In Experiment 1, participants heard predictive sentences like 'What the librarian will read, which is shown here, is the…' and viewed visual arrays (e.g., see Figure 1) with predictable targets like a book and phonological competitors like a bull or unrelated distractors like a goat. In Experiment 2, to assess task effects, these trials were interleaved with a cloze procedure. If comprehenders generate lexical predictions during sentence processing, participants were expected to make (i.e., predictive) mouse cursor movements to phonological competitors before hearing predictable target words (e.g., "book").

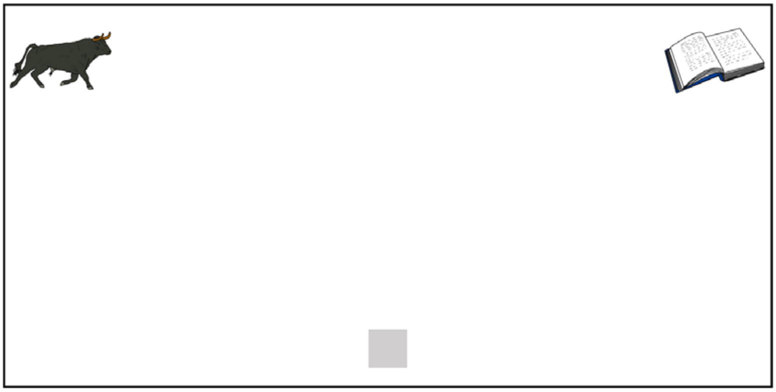

Figure 1. Object visual array depicting the predictable target book and phonological competitor bull for the example sentence, "What the librarian will read, which is shown here, is the book.".

2. Experiment 1

Experiment 1 assessed lexical prediction by measuring mouse cursor movements to phonological competitors (e.g., bull) of predictable targets (e.g., “What the librarian will read, which is shown here, is the…”). Crucially, participants’ (i.e., predictive) mouse cursor movements were assessed before they heard predictable target words (e.g., “book”). This experiment was pre-registered (https://osf.io/93mja) and the data and analysis code are available at OSF (https://doi.org/10.17605/OSF.IO/G48CQ).

Method

Participants

Fifty-two monolingual English speakers from the UK with normal or corrected-to-normal vision and hearing (age M = 37.77, SD = 12.18; 37 female, 14 male, 1 other) were recruited from prolific.com. The sample size enabled detection of an average two-level within-participants psychological effect size (d_z = 0.40, power = 0.80, alpha = 0.05; Brysbaert, 2019).

Design and materials

Object type (phonological competitor and unrelated distractor) was manipulated within participants. Twenty-eight object sets were created, which each included a target (e.g., book), phonological competitor (e.g., bull), and unrelated distractor (e.g., goat) from the MultiPic databank of visual stimuli (Duñabeitia et al., 2018). Targets and phonological competitors shared an onset (e.g., bʊ…), which was not shared with unrelated distractors. A predictive sentence (e.g., “What the librarian will read, which is shown here, is the book.”), in which both a noun/NP (e.g., “librarian”) and verb/VP (e.g., “read”) were associated with the target, was recorded for each object set using a synthesised text-to-speech Neural2 voice. The mean sentence duration was 4.51 seconds, and the mean onsets of ‘which’ and the target (e.g., “book”) were 2.21 and 3.97 seconds, respectively. Based on latent semantic analysis (e.g., Landauer & Dumais, 1997), phonological competitors and unrelated distractors were closely matched in their semantic relatedness to targets (competitors: M = 0.11, SD = 0.08; distractors: M = 0.08, SD = 0.07), target-associated nouns (competitors: M = 0.07, SD = 0.07; distractors: M = 0.07, SD = 0.09), and target-associated verbs (competitors: M = 0.09, SD = 0.07; distractors: M = 0.10, SD = 0.09) (cosines were unavailable for barista or shapeshift). Objects were used as both phonological competitors and unrelated distractors across targets, controlling non-target properties. Two counterbalanced lists (e.g., see Table 1 of the Appendix for the full list of stimuli) were created, which each included all 28 target and 28 non-target objects and paired one half of targets with phonological competitors and the other half with unrelated distractors. Each target was paired with both its phonological competitor and unrelated distractor across lists.

Procedure

The internet-mediated experiment was created in PsychoPy (Peirce et al., 2019) and run on pavlovia.org. Participants were presented with one practice trial followed by 28 experimental trials. On each trial, participants were presented a blank visual array followed by an object visual array like Figure 1. Visual arrays used normalised coordinates ranging from −1 to 1. In object visual arrays, a target and either phonological competitor or unrelated distractor were presented, sized 0.30 × 0.60 (i.e., in normalised units, reflecting 0.30/2 = 15% of the width of the visual display and 0.60/2 = 30% of the height of the visual display) and centred at (±0.85, 0.70). In blank visual arrays, each object was replaced with a shaded box. Participants clicked on an icon at the bottom of the visual display (0, −0.85) to begin each trial. Each trial began with the blank visual array. After 0.50 seconds, participants heard the (i.e., predictive) sentence. At the onset of ‘which’ in the sentence, participants were presented the object visual array. Thus, following Ito et al. (2018), the visual array did not provide information relevant to the target until after the target-associated noun and verb (e.g., “librarian will read…”) were heard. Participants were instructed to click on the (i.e., target) object referred to in each sentence. Trial order and object location were randomised.

Results

One participant who did not complete the experiment and three participants whose data was sampled at less than 30 Hz were removed from the analysis. Mean accuracy was 99.92% (*SD* = 0.52), which is comparable to Kukona (2020, 2023; e.g., >99%). Inaccurate trials and trials with log RTs more than 2.5 standard deviations above the global mean were also removed from the analysis (0.82%). Figure 2A depicts mean trajectories across the visual array by object type. Trajectories were aggregated by dividing each trial into 101 normalised time slices and inverting the horizontal axis for targets on the left (e.g., see Spivey et al., 2005). Normalised coordinates were only used to depict participants’ mean trajectories across the visual array and were not analysed statistically. Figure 2B depicts mean horizontal × coordinates by object type in 0.10 time slices from 2 seconds before target onset to 1 second afterward. Positive horizontal × coordinates reflect attraction to targets, while negative horizontal × coordinates reflect attraction to non-targets.

The analysis focused on (i.e., raw) horizontal × coordinates during the two second time window preceding the onset of the target (e.g., depicted in Figure 2B), which reflected (i.e., predictive) behaviours typically just after hearing the target-associated noun and verb (e.g., “librarian will read…”) but always before hearing the target (e.g.,

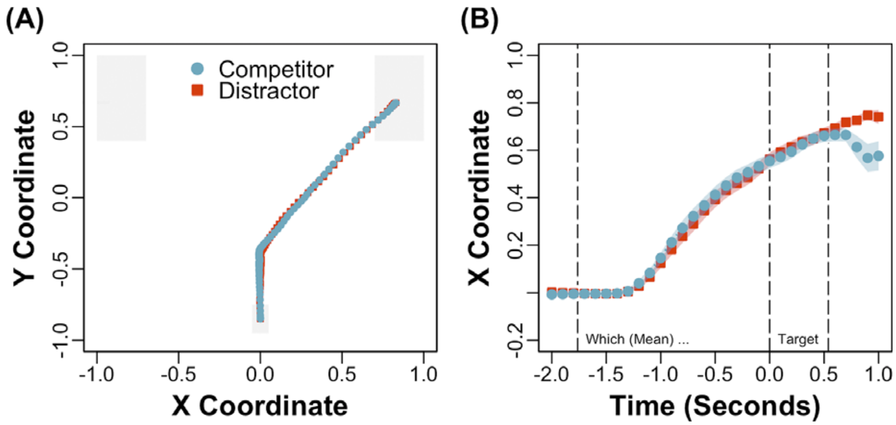

Figure 2. Time-normalised mean mouse cursor trajectories across the visual array (A) and mean (shaded bands show SEs) horizontal mouse cursor movements (i.e., x coordinates) from 2 seconds before the onset of the predictable target word (e.g., "book") to 1 second afterward (B) with phonological competitors (e.g., bull) versus unrelated distractors (e.g., goat) in Experiment 1.

“book”). A (i.e., mean) predictive horizontal × coordinate was calculated for each trial by averaging across the within-trial horizontal × coordinates during the (i.e., predictive) time window. Log RTs were computed from the onset of ‘which’. No responses were made before the onset of ‘which’, but 14.45% of responses were made before the onset of the target; on these trials, predictive horizontal × coordinates were averaged up to a response was made. In addition, 38.23% of responses were made before the offset of the target/sentence.

Following the preregistration plan for this experiment, trial-level predictive horizontal × coordinates and RTs were submitted to linear mixed effects models with deviation-coded fixed effects of object type (phonological competitor = −0.5, unrelated distractor = 0.5) and random intercepts and slopes by participants and items. Models were run in R using lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017), and their random effects were simplified when there were issues with fit. The analysis of predictive horizontal × coordinates revealed a significant intercept, $Est. = 19.09 \times 10^{-2}$, $SE = 1.49 \times 10^{-2}$, $t(57.84) = 12.78$, $p < 0.001$, such that trajectories were attracted to targets over non-targets, and a non-significant effect of object type, $Est. = -0.89 \times 10^{-2}$, $SE = 1.20 \times 10^{-2}$, $t(25.04) = -0.74$, $p = 0.46$, such that trajectories did not differ between phonological competitors ($M = 0.20$, $SD = 0.11$) and unrelated distractors ($M = 0.19$, $SD = 0.10$). Likewise, the analysis of RTs (which excluded random slopes by participants due to issues with fit) revealed a non-significant effect of object type, $Est. = -0.44 \times 10^{-2}$, $SE = 1.41 \times 10^{-2}$, $t(25.87) = -0.31$, $p = 0.76$, such that RTs did not differ between phonological competitors ($M = 2.42$, $SD = 0.44$) and unrelated distractors ($M = 2.39$, $SD = 0.43$).

As an exploratory analysis, Bayes factors were also computed by aggregating predictive horizontal × coordinates and RTs by participants and submitting these to participant *t*-tests comparing phonological competitors and unrelated distractors. The analysis of both predictive horizontal × coordinates, $t(47) = 0.82$, $p = 0.42$, $d_x = 0.12$, $BF_{01} = 4.65$, and RTs, $t(47) = 0.90$, $p = 0.37$, $d_x = 0.13$, $BF_{01} = 4.36$, provided substantial support ($BF_{01} > 3$) for a null effect. Finally, maximum signed deviations were also analysed, which did not yield significant experimental effects; this is included in the analysis code.

Discussion

Participants hearing predictive sentences like ‘What the librarian will read, which is shown here, is the…’ made mouse cursor movements to predictable objects like a book rather than a bull or goat. Consistent with Kukona (2023), these results reveal that comprehenders generate predictions during sentence processing and that comprehenders’ mouse cursor movements are sensitive to these predictions. However, lexical prediction, as reflected in mouse cursor movements to phonological competitors like a bull, was not observed; rather, exploratory Bayes factors provide evidence against predictive phonological competition. These results suggest that participants generated conceptual but not lexical predictions, pre-activating the semantics but not forms of words.

Experiment 2 aimed to build on Experiment 1 by assessing task effects. In Experiment 2, mouse cursor tracking trials (i.e., from Experiment 1) were interleaved with a cloze procedure, which explicitly tasked participants with activating word forms that were predictable given a sentence fragment. Inspired by Pickering and Gambi (2018; also see Hintz et al., 2016), if explicit engagement in a cloze procedure boosts lexical prediction (e.g., across trials), participants were expected to make predictive mouse cursor movements to phonological competitors on interleaved mouse cursor tracking trials.

3. Experiment 2

Experiment 2 again assessed lexical prediction by measuring mouse cursor movements to phonological competitors of predictable targets. As in Experiment 1, participants' (i.e., predictive) mouse cursor movements were assessed before they heard predictable target words. To assess task effects, these trials were interleaved with a cloze procedure that tasked participants with completing similar sentences (e.g., "What the librarian will read is this."). This experiment was pre-registered (https://osf.io/e96j5) and the data and analysis code are available at OSF (https://doi.org/10.17605/OSF.IO/G48CQ).

Method

Participants

Fifty-two participants (age *M* = 36.24, *SD* = 10.23, 1 unreported; 28 female, 23 male, 1 other) were recruited following the same criteria as Experiment 1.

Design and materials

In contrast to Experiment 1, the task was manipulated within participants. On one half of trials, participants performed the mouse cursor tracking task from Experiment 1. On the other half of trials, they performed a cloze procedure. For the mouse cursor tracking task, the design and materials were the same as Experiment 1. For the cloze procedure, each predictive sentence was modified to include the target-associated noun/NP and verb/VP but not the target (e.g., "What the librarian will read is this.").

Four counterbalanced lists were created with all 28 targets, which presented one half of targets in the mouse cursor tracking task and the other half in the cloze procedure and paired one half of targets in the former with its phonological competitor and the other half with its unrelated distractor. Each target was presented in both tasks and paired with both non-targets across lists.

Procedure

The internet-mediated experiment was again created in PsychoPy (Peirce et al., 2019) and run on pavlovia.org. Participants were presented with one practice trial from each task (i.e., two practice trials total) followed by 14 experimental trials from each task (i.e., 28 experimental trials total). The tasks were randomly interleaved. Participants clicked on an icon at the bottom of the visual display (0, −0.85) to begin each trial. For the mouse cursor tracking task, the procedure was the same as Experiment 1. For the cloze procedure, each trial began with the blank visual array. After 0.50 seconds, participants heard the (i.e., cloze) sentence. At the onset of 'is' in the sentence, participants were presented a text entry box. Participants were not presented with any objects. Thus, information about the task was not provided until after the target-associated noun and verb (e.g., "librarian will read…") were heard. Participants were instructed to type the first word(s) to come to mind.

Results

In the cloze procedure, the target reflected the modal response for 85.71% of sentences. The mean percentage of responses reflecting the target (i.e., the cloze probability) was 77.30% (*SD* = 23.08, Min = 32.26%, Max = 100.00%). Probabilities are reported by sentence in the appendix.

In the mouse cursor tracking task, two participants whose data was sampled at less than 30 Hz were removed from the analysis. Mean accuracy was 100% (*SD* = 0.00). Trials with log RTs more than 2.5 standard deviations above the global mean were also removed from the analysis (1.57%). Figure 3A depicts mean trajectories across the visual array by object type, and Figure 3B depicts mean horizontal × coordinates by object type. No responses were made before the onset of 'which', but 38.97% of responses were made before the onset of the target, and 56.74% of responses were made before the offset of the target/sentence.

Following the preregistration plan for this experiment, trial-level predictive horizontal × coordinates and RTs were submitted to similar analyses to Experiment 1. The analysis of predictive horizontal × coordinates revealed a significant intercept, $Est. = 23.01 \times 10^{-2}$, $SE = 1.35 \times 10^{-2}$, $t(51.77) = 17.08$, $p < 0.001$, such that trajectories were attracted to targets over non-targets, and a non-significant effect of object type, $Est. = -0.90 \times 10^{-2}$, $SE = 1.39 \times 10^{-2}$, $t(20.74) = -0.65$, $p = 0.52$, such that trajectories did not differ between phonological competitors ($M = 0.24$, $SD = 0.09$) and unrelated distractors ($M = 0.22$, $SD = 0.10$). Likewise, the analysis of RTs (which excluded random slopes by participants due to issues with fit) revealed a non-significant effect of object type, $Est. = 0.89 \times 10^{-2}$, $SE = 2.76 \times 10^{-2}$, $t(24.27) = 0.32$, $p = 0.75$, such that RTs did not differ between phonological competitors ($M = 2.13$, $SD = 0.66$) and unrelated distractors ($M = 2.13$, $SD = 0.64$).

As an exploratory analysis, Bayes factors were also computed by aggregating predictive horizontal × coordinates and RTs by participants and submitting these to participant *t*-tests comparing phonological competitors and unrelated distractors. The analysis of both predictive horizontal × coordinates, $t(49) = 0.88$, $p = 0.38$, $d_x = 0.13$, $BF_{01} = 4.50$, and RTs, $t(49) = -0.08$, $p = 0.93$, $d_x = -0.01$, $BF_{01} = 6.48$, provided substantial support ($BF_{01} > 3$) for a null effect.

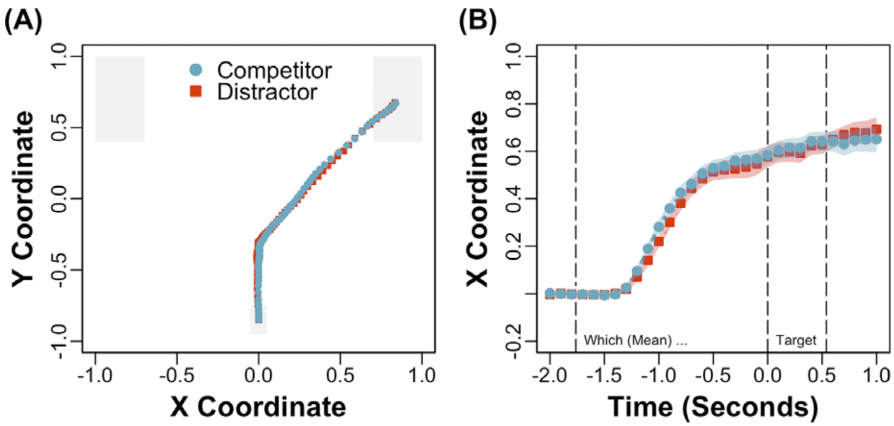

Figure 3. Mouse cursor trajectories across the visual array (A) and horizontal mouse cursor movements from 2 seconds before the onset of the predictable target word (B) with phonological competitors versus unrelated distractors in Experiment 2.

In addition, predictive horizontal × coordinates and RTs were combined across experiments and submitted to linear mixed effects models with deviation-coded fixed effects of object type and experiment (E1 = -0.5, E2 = 0.5), as well as their interaction and random intercepts and slopes by participants and items. The analysis of predictive horizontal × coordinates (which was simplified to included random intercepts by participants and items and random slopes by items for object type due to issues with fit) revealed a significant intercept, $Est. = 21.02 \times 10^{-2}$, $SE = 1.11 \times 10^{-2}$, $t(84.24) = 18.98$, $p < 0.001$, and a significant effect of experiment, $Est. = -3.85 \times 10^{-2}$, $SE = 1.80 \times 10^{-2}$, $t(99.20) = -2.14$, $p < 0.05$, such that trajectories were attracted to targets over non-targets in both experiments, and this attraction was also greater in Experiment 2 than 1. In contrast, the analysis revealed a non-significant effect of object type, $Est. = -0.89 \times 10^{-2}$, $SE = 0.96 \times 10^{-2}$, $t(32.89) = -0.93$, $p = 0.36$, and interaction, $Est. = 0.01 \times 10^{-2}$, $SE = 1.73 \times 10^{-2}$, $t(121.82) = 0.00$, $p = 1.00$. Likewise, the analysis of RTs (which was simplified to included random intercepts by participants and items due to issues with fit) revealed a significant effect of experiment, $Est. = 17.10 \times 10^{-2}$, $SE = 5.38 \times 10^{-2}$, $t(95.03) = 3.18$, $p < 0.01$, such that RTs were faster in Experiment 2 than 1, and a non-significant effect of object type, $Est. = 0.07 \times 10^{-2}$, $SE = 1.58 \times 10^{-2}$, $t(28.93) = 0.04$, $p = 0.97$, and interaction, $Est. = -1.02 \times 10^{-2}$, $SE = 2.23 \times 10^{-2}$, $t(1895.33) = -0.46$, $p = 0.65$. Finally, maximum signed deviations were also analysed, which did not yield significant experimental effects; this is included in the analysis code.

Discussion

Consistent with Experiment 1, participants made predictive mouse cursor movements to targets but not phonological competitors. These results again suggest that participants pre-activated the semantics but not forms of words. In addition, while the interleaved cloze procedure did not affect mouse cursor movements to phonological competitors, it did facilitate both mouse cursor movements to targets and RTs, suggesting that predictive sentence processing is sensitive to task. Finally, the cloze procedure confirmed that targets were predictable on average (e.g., in comparison, a criterion of 67% is reported by Luke & Christianson, 2016).

4. General discussion

Two mouse cursor tracking experiments investigated lexical prediction. Participants hearing predictive sentences like ‘What the librarian will read, which is shown here, is the…’ made predictive mouse cursor movements to predictable targets like a book but not phonological competitors like a bull (e.g., versus unrelated distractors like a goat). These results provide novel insight into predictive sentence processing, suggesting that varieties of prediction are distinguished by motor movements of the hand but also raising questions about the pervasiveness and importance of lexical prediction.

These results complement a range of findings from the psycholinguistic literature. Participants generated predictions (e.g., reflecting verb selectional restrictions), complementing Altmann and Kamide (1999), and their mouse cursor movements were sensitive to these predictions, complementing Kukona (2023). Moreover, participants in Experiment 1 activated phonological competitors after target word onset (e.g., reflective of spoken word recognition), complementing Spivey et al.

(2005); as depicted in Figure 2B, mouse cursor trajectories were attracted to phonological competitors (M = 0.70, SD = 0.16) over unrelated distractors (M = 0.75, SD = 0.10) from 0.50 to 1 second after target word onset, $t(45) = -2.26$, $p < 0.05$. Finally, mouse cursor movements to phonological competitors before target word onset, reflecting lexical predictions, were not observed, complementing Nieuwland et al. (2018).

These results also contrast with a growing body of evidence for lexical prediction from the visual world paradigm (e.g., Ito et al., 2018; Kukona, 2020; Li et al., 2022; Li & Qu, 2024; Xu et al., 2024; Zhao et al., 2023). There is perhaps no doubt that comprehenders can activate word forms (e.g., reflecting their phonology and/or orthography) that are predictable given a sentence fragment, which they robustly do in the cloze procedure. Moreover, Ito (2024) conducted a meta-analysis on studies addressing predictive phonological competition in the visual world paradigm (e.g., including Ito et al., 2018) and found a small but significant (e.g., lexical prediction) effect. Thus, even outside a cloze procedure, comprehenders can pre-activate word forms that are predictable. However, the results of Experiments 1 and 2 suggest that the pre-activation of word forms may be optional rather than necessary, complementing Pickering and Gambi (2018). This optionality may depend on a range of factors (e.g., timing, cognitive resources, etc.), but a factor highlighted by these results is lexical predictability. Relatedly, cloze probability was a significant mediator of the predictive phonological competition effect in Ito's (2024) meta-analysis, which was based on studies with mean cloze probabilities ranging from 85% to 98%. The mean cloze probability in Experiments 1 and 2 was just outside this range (i.e., 78%), which may explain these (e.g., null) results. However, a limitation of this study is that lexical predictability was not manipulated systematically (e.g., experimentally). Thus, an important direction for future research will be to carefully address the (e.g., quantitative) relationship between lexical predictability and lexical prediction.

The literature distinguishes varieties of prediction. For example, Pickering and Gambi (2018) distinguish prediction-by-production from prediction-by-association, and Luke and Christianson (2016) distinguish lexical prediction from graded prediction (e.g., also see Huettig, 2015). Relatedly, an important difference between Nieuwland et al. (2018) and these experiments is that while neither supported lexical prediction, these results robustly support (e.g., non-lexical) pre-activation. Pickering and Gambi (2018) argue that prediction-by-production, which relies on production processes, 'constitutes the most effective mechanism for prediction during language comprehension' (p. 1014). However, these results highlight a potential important caveat: lexical prediction may be an extreme rarity that is only effective when cloze probabilities approach ceiling. Based on a more generous criterion (i.e., a cloze probability above 67%), Luke and Christianson (2016) estimated that predictable words comprised only 5% of content words, suggesting that lexical prediction may be extremely rare.

We conjecture that these results are underpinned by conceptual predictions, such that participants pre-activated the semantics but not forms of words. Relatedly, Luke and Christianson (2016) describe graded prediction as the prediction of linguistic features, and Pickering and Gambi (2018) hypothesise that comprehenders can generate predictions during sentence processing based on spreading activation among associated concepts in memory, which they term prediction-by-association. Accordingly, participants in Experiments 1 and 2 may have pre-activated the concept of a book when hearing 'the librarian will read…' based on spreading activation among the concepts (e.g., or features; Luke & Christianson, 2016) corresponding to librarian, read and book without necessarily pre-activating the word 'book'. Supporting prediction-by-association, Kukona et al. (2014) found that participants pre-activated associated but unpredictable concepts. Their participants heard predictive sentences like 'The boy will eat the white…' and viewed visual arrays with predictable targets like a white cake, adjective-associated competitors like a white car and other unrelated distractors. Before hearing the predictable target word (e.g., "cake"), participants predictively fixated the competitor, suggesting that associated but unpredictable concepts were pre-activated (e.g., also see Kukona et al., 2016; Langlois et al., 2024; Nozari et al., 2016; Prystauka et al., 2024; Stone et al., 2021). Moreover, this variety of prediction may constitute an especially effective mechanism for prediction in these experiments and the visual world paradigm generally, because associations between the unfolding language and visual stimuli can guide prediction. However, semantically associated competitors were not included in this study, so it provides only indirect evidence of graded prediction and/or prediction-by-association.

These results also suggest that predictive behaviours are task-sensitive. In Experiment 2, mouse cursor tracking trials were interleaved with a cloze procedure, and both mouse cursor movements to targets and RTs were facilitated. In addition, Figure 3B suggests that mouse cursor movements were not attracted to phonological competitors after target word onset, which may be because over 50% of responses were made before target word offset (e.g., versus under 40% in Experiment 1). These results complement Hintz et al. (2016), whose participants read predictable (e.g., "the man breaks … a glass") or non-predictable (e.g., "the man borrows … a glass") sentences. When participants performed a self-paced reading task interleaved with a naming task, reading times were facilitated on predictable sentences in the former, but when participants only performed a self-paced reading task, this facilitation was not observed. Taken together, Hintz et al. (2016) and Experiment 2 support a link between prediction and production, suggesting that engaging in the latter may facilitate the former across trials, although neither provides specific support for lexical prediction.

This study also highlights important methodological considerations. An important difference between these experiments and Ito et al. (2018) is that the latter did not depict targets and competitors together in the same visual array. One potential limitation of mouse cursor tracking is that targets are typically depicted with competitors to provide a destination for participants' mouse cursor movements, which may swamp potential competitor effects (e.g., see Ito, 2024). Thus, how lexical prediction is affected by the visual array is a potential direction for future research. Relatedly, factors such as participants' screen sizes, whether participants used a mouse or trackpad and whether participants used speakers or headphones were uncontrolled in this internet-mediated study. Thus, how lexical prediction is affected by these uncontrolled factors remains unresolved. Nevertheless, complementing Kukona (2023), these results again suggest that internet-mediated mouse cursor tracking is sensitive to at least some aspects of predictive sentence processing. In addition, while lexical prediction was not observed in this study, Experiment 1 afforded more power than Ito et al. (2018), with more participants (e.g., 52 versus 24) and items (e.g., 28 versus 16; although the latter was halved in Experiment 2). Relatedly, Ito's (2024) meta-analysis also emphasises that more careful attention to power is necessary in future research.

In conclusion, these results suggest that varieties of prediction are distinguished by motor movements of the hand, such that participants generated conceptual but not lexical predictions. Complementing Pickering and Gambi (2018), these results suggest that lexical prediction may be optional rather than necessary. Finally, complementing Kukona (2023), these results also suggest that mouse cursor tracking is a powerful tool for investigating predictive sentence processing.

Data availability statement. The data and analysis code are available at OSF (https://doi.org/10.17605/OSF.IO/G48CQ).

Competing interest. The author declares none.

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Appendix

Table 1 reports predictive sentences, predictable targets, phonological competitors and unrelated distractors from Experiments 1 and 2, as well as target cloze probabilities from Experiment 2.

Table 1. Stimuli from Experiments 1 and 2

Item	Sentence	Target	Competitor	Distractor	Cloze
1	What the runner will sprain, which is shown here, is her ankle	ankle	anchor	coffin	0.94
2	What the vampire will shapeshift into, which is shown here, is the bat	bat	back	cork	0.74
3	What the tired woman will sleep in, which is shown here, is the bed	bed	bell	pig	0.91
4	What the explosives engineer will disarm, which is shown here, is the bomb	bomb	box	camel	1.00
5	What the librarian will read, which is shown here, is the book	book	bull	goat	1.00
6	What the photographer will take a picture with, which is shown here, is the camera	camera	camel	box	1.00
7	What the barista will grind, which is shown here, is the coffee	coffee	coffin	anchor	0.87
8	What the farmer will husk, which is shown here, is the corn	corn	cork	back	0.44
9	What the vet will play fetch with, which is shown here, is the dog	dog	doll	witch	0.47
10	What the cemetery will be haunted by, which is shown here, is the ghost	ghost	goat	bull	0.95
11	What the bird will lay an egg in, which is shown here, is the nest	nest	net	shield	1.00
12	What the patient will swallow, which is shown here, is the pill	pill	pig	bell	0.65
13	What the border collie will herd, which is shown here, is the sheep	sheep	shield	net	0.97
14	What the bird will flap, which is shown here, is its wing	wing	witch	doll	1.00
15	What the player will kick, which is shown here, is the ball	ball	boy	lamp	0.84
16	What the woman in the park will sit on, which is shown here, is the bench	bench	belt	whale	0.95
17	What the cleaner will empty, which is shown here, is the bin	bin	bib	mouth	0.69
18	What the dog will bury, which is shown here, is the bone	bone	boat	sword	1.00
19	What the milkmaid will churn, which is shown here, is the butter	butter	button	cannon	0.41
20	What the birthday girl will blow out, which is shown here, is the candle	candle	cannon	button	0.94
21	What the bear will hibernate in, which is shown here, is the cave	cave	cage	road	0.67
22	What the castaway on the island will crack, which is shown here, is the coconut	coconut	koala	devil	0.74
23	What the cactus will grow in, which is shown here, is the desert	desert	devil	koala	0.32

(*Continued*)

Table 1. (*Continued*)

Item	Sentence	Target	Competitor	Distractor	Cloze
24	What the experiment will be conducted in, which is shown here, is the lab	lab	lamp	boy	0.63
25	What the cat will chase, which is shown here, is the mouse	mouse	mouth	bib	0.75
26	What the girl playing tug of war will pull on, which is shown here, is the rope	rope	road	cage	1.00
27	What the tree will be cut with, which is shown here, is the saw	saw	sword	boat	0.33
28	What the surfer will ride, which is shown here, is the wave	wave	whale	belt	0.44

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