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The contribution of learning and memory processes to verb-specific syntactic processing

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ABSTRACT

Certain aspects of lexical knowledge can be primed by recent usage, with effects observed up to 24 h later in some circumstances. Here, we used syntactically ambiguous sentences ("The man hit/chose the dog with the stick") to explore the longevity of priming of syntactic structure. Some verbs provide a bias towards an instrument interpretation (the stick was used to *hit* the dog), whilst others are biased towards the modifier interpretation (the man *chose* the dog that possessed the stick). Experiment 1 revealed an effect of pre-existing verb bias on resolving syntactic ambiguities. In Experiment 2, we primed specific verbs towards their dispreferred interpretation in an exposure phase (e.g., *hit* was primed to the modifier interpretation). ~ 20 min later, the same verbs, along with unprimed verbs, were encountered in syntactically ambiguous contexts in a test phase. Exposure to the dispreferred interpretation in the exposure phase increased the preference for the same interpretation in the test phase, particularly for instrument-biased verbs. In Experiment 3, the exposure and test phases were separated by a ~ 12-hour interval that included sleep. No overall effect of exposure was found, but again a simple effect of priming was found for instrument-biased verbs. Finally, in Experiment 4 using a sentence completion task, we found that instrument-biased verbs had significantly stronger pre-existing biases, which we discuss as a possible explanation for the imbalance in priming between verb bias conditions. Our results suggest verb-bias priming is maintained over relatively long periods such as 20 min, and possibly as long as 12 h, consistent with a contribution of episodic memory to maintenance of verb-specific syntactic biases.

Introduction

Language can often present syntactically ambiguous situations. Consider, for example, a sentence containing a *with* prepositional phrase such as "the man rubbed the frog with the bottle". This phrase is syntactically ambiguous in that there are at least two possible interpretations: First, the prepositional phrase "with the bottle" could attach to the verb (*rub*), such that the bottle is used as an instrument to rub the frog, or it could attach the noun (*frog*), such that the man rubs the frog that is in possession of the bottle. Here, we refer to these two alternatives as *instrument* and *modifier* interpretations, respectively (Ryskin et al., 2017). Given this ambiguity, individuals must arrive at a contextually-appropriate interpretation relatively quickly in order to comprehend language efficiently.

A wealth of evidence indicates that one key factor in resolving this kind of ambiguity is the identity of the verb (Boland et al., 1995; Trueswell et al., 1993). Whereas the verb *rubbed* may not provide a strong bias in either direction, other verbs might provide biasing information in favour of the instrument (e.g., *hit*) or modifier (e.g., *chose*) interpretation. This verb-specific bias is readily exploited during comprehension to aid interpretation (Snedeker & Trueswell, 2004), suggesting that language users build up lexical knowledge about verbs across development that provides a key source of information about how to resolve any upcoming syntactic ambiguities.

A series of studies by Ryskin and colleagues suggested that these biases remain malleable into adulthood. In a norming experiment, Ryskin et al. (2017) instructed participants to complete a series of sentence fragments (e.g., "He will *X* the dolphin…") containing various

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verbs. Based on the responses, verbs were classified into three categories: (1) *Pre-existing instrument-biased*, representing verbs that tended to elicit responses with an instrument continuation (e.g., "He will *hit* the dolphin… with the sonar machine"), (2) *Pre-existing modifier-biased*, representing verbs that tended to elicit responses with a modifier continuation (e.g., "He will *choose* the dolphin… with the missing fin"), and (3) *equi-biased*, representing verbs that tended to elicit both types of responses (e.g., *rub*).

Subsequently, Ryskin et al. (2017; Experiment 1) tested for an effect of verb bias on syntactic ambiguity resolution using a visual-world paradigm. Here, participants enacted verbal instructions containing different verbs (e.g., "*hit/choose* the dog with the stick") by interacting with visual stimuli on a computer screen. Crucially, each syntactic interpretation of the instruction was consistent with a visual stimulus. For example, an image of a dog in possession of a stick was present which could be selected (modifier interpretation), as well as the image of a stick in isolation, that could be used to *hit/choose* a dog (instrument interpretation). Based on eye-tracking and mouse clicking measures, it was found that verbs classified as having a pre-existing instrument bias elicited more frequent instrument interpretations than verbs classified as having a pre-existing modifier bias.

Crucially, Experiment 2 of Ryskin et al. (2017) showed that these biases are malleable, and that recent exposure can alter a person's tendency to interpret a verb as indicating an instrument or a modifier interpretation. The experiment made use of eight equi-biased verbs. On prime trials, verbs were biased towards one particular interpretation by presenting visual stimuli in a way that constrained the verb towards the intended interpretation. For example, upon hearing the phrase "I know! You should rub the bunny with the bottle", participants viewed an image of a bunny and a separate image of a bottle, rather than an image of a bunny possessing a bottle. In this example, an instrument interpretation of the verb was primed, in that the bottle should be used to rub the bunny. On test trials, which were intermixed with the prime trials, the same verb was presented again but both interpretations were viable given the on-screen images (i.e., an image of a bunny in possession of a bottle was also present). The researchers found that verbs primed towards a particular interpretation on prime trials were more likely to be interpreted in the same way on test trials. We refer to this as *verb-bias priming*.

This result is important because it suggests that specific verb biases can be altered based on recent experience of their usage, and perhaps provides a mechanism by which long-term knowledge about verb biases can be updated. This kind of priming complements the more abstract syntactic or structural priming in which previously encountered syntactic structures are more likely to be reproduced (Bock, 1986; 1989; Mahowald et al., 2016; Pickering & Branigan, 1998) and are processed more efficiently (e.g., Arai et al., 2007; Boudewyn et al., 2014; Kaschak et al., 2014; Ledoux et al., 2007; Tooley & Traxler, 2010; Tooley et al., 2019) compared to instances when the same structure is not previously encountered, which generalises across lexical items (Hartsuiker et al., 2008).

Two key questions remain with respect to the relationship between specific verb-bias priming and updating of long-term knowledge. First, the longevity of priming remains unclear: for the priming to be considered as a form of updating across the lifespan, it should be observable over reasonably long periods of time. Second, the memory mechanism(s) underpinning this kind of priming are unknown. The current study aims to address these questions.

On the issue of longevity, Ryskin et al. (2017) observed priming across lags of several intervening trials (median = 6). Such longevity weakens the possibility that the priming could be explained as a form of residual activation of nodes in a lexical network. Residual activation has been argued to underpin a different kind of priming, in which syntactic priming produces particularly strong facilitation of subsequent processing when the specific verb is also repeated (*lexical boost*; Pickering & Branigan, 1998). Residual activation would be expected to dissipate quickly on processing of subsequent sentences (see also Collins & Loftus, 1975, for similar assumptions in the semantic/lexical domain), and there is indeed support for the claim that the lexical boost dissipates quite quickly (Mahowald et al., 2016). Hartsuiker et al. (2008), for example, revealed that compared to instances where test trials appear immediately after prime trials, the magnitude of the lexical boost weakened substantially with the introduction of two filler trials, and further still with six interleaving fillers. That said, the Ryskin et al. methodology is different in an important way in that it uses eight repeated prime trials for each verb. Thus, residual activation might build up across separate prime trials, gradually reducing a critical threshold for verb-structure comprehension that may bias the online interpretation of a syntactically ambiguous scene.

Relevant to the second question, Ryskin et al. (2018) considered the role of episodic/declarative memory systems in verb-bias priming by measuring priming in amnesic patients with hippocampal damage. It was predicted that if verb-bias priming is at least partly dependent on the hippocampus and surrounding structures (i.e., brain regions involved in episodic memory), then priming should be weaker or absent in amnesic patients relative to age-matched healthy controls (mean age of controls = 59 years). Consistent with this prediction, the amnesic patients showed no significant verb-bias priming, but in fact the age-matched controls also showed no priming effects, conflicting with Ryskin et al. (2017) who recruited younger, undergraduate participants. Given the small sample size in Ryskin et al. (2018) of three participants per group, one possibility is that the absence of priming in the healthy control group may reflect a Type-II error, and priming could have emerged in a larger sample and/or in a different group of three participants. Alternatively, the absence of priming may reflect shared deficits in hippocampal functioning across participant groups, given that the hippocampus is subject to structural and functional decline with age (Bettio et al., 2017). Compared to the undergraduate participants who showed verb-bias priming in Ryskin et al. (2017), the older participants in Ryskin et al. (2018) may therefore experience more limited hippocampal and episodic memory functioning, potentially impairing the binding of verb-structure information. Overall, the picture built up from the two Ryskin studies is that verb-specific biases in comprehension are malleable to a certain extent, with priming effects seen across at least eight or so trials within a session in young adults. There is also some evidence that this malleability may be supported by the hippocampus, but at this point, the support for this proposal is modest.

Verb-specific biases are seen as relevant to the syntactic domain of comprehension, but they have a strong parallel in the lexical-semantic domain. Just as verbs like *rub* can be ambiguous in terms of their syntactic role in a sentence, nouns such as *bank* have ambiguity in their semantic interpretation. Whilst the most frequently used meaning of a homonym such as bank (e.g., a financial institution) is often the most accessible (Rodd, 2020; Vitello & Rodd, 2015), studies have revealed that recent encounters with less frequent, subordinate meanings (e.g., the bank of a river) increase the likelihood of the same meaning being adopted when the ambiguous word is encountered at a later point (Betts et al., 2018; Blott et al., 2022; Gaskell et al., 2019; Gilbert et al., 2018; 2021; Parker et al., 2023; Rodd et al., 2013; 2016). Therefore, there appears to be some malleability in the semantic interpretation of words, just as there is malleability in their syntactic interpretation.

The literature on this *word-meaning priming* effect is somewhat further advanced on the questions of longevity and memory mechanisms raised earlier. For example, Rodd et al. (2016) showed that word-meaning priming could be observed up to 40 min after initial exposure to the subordinate meaning, which is well beyond the range for which a residual activation account can be applied. Nonetheless, priming tends to decay across time within a day (Rodd et al., 2016), and is stabilised by a period of sleep soon after exposure, meaning that it could be observed 12 or 24 h later (Gaskell et al., 2019). In contrast, word-meaning priming diminished across 12 h awake.

In terms of memory mechanisms, some authors (Gilbert et al., 2018;

Rodd et al., 2016) have argued that word-meaning priming is explained by an *immediate alteration account* in which lexical knowledge about the meaning of the word is updated following the initial encounter. Modelled within a distributed connectionist framework (Rodd et al., 2004), exposure to the subordinate meaning of an ambiguous word alters the strength of connections between lexical units, increasing the probability of the semantic system settling onto the primed meaning when the same word is encountered at a later point. This account explains the longevity of word meaning priming, although it is harder to explain why priming effects decay across time spent awake.

A later alternative account focused on the stabilising effect of sleep on word-meaning priming (Gaskell et al., 2019). According to the *episodic context account*,[1] when first encountering an ambiguous word in its subordinate form, the language user encodes a context-specific representation of the linguistic episode, which binds together elements of the discourse. This representation serves to support future linguistic experiences involving the same word, alongside long-term lexical knowledge. This would explain why word-meaning priming is observed in the minutes and potentially hours following exposure to an ambiguous word. Crucially, however, context-specific episodic representations may be subject to sleep-related consolidation, in which sleep facilitates the consolidation and integration of encoded episodic memories into long-term cortical knowledge (McClelland et al., 1995; Paller et al., 2021; Rasch & Born, 2013; Stickgold, 2005). In the absence of sleep-related consolidation, episodic representations are likely to decay (Hardt et al., 2013), limiting the utility of these memories in supporting future linguistic interactions. Also consistent with the episodic context account, it appears that lexical semantic representations are compromised in patients with amnesia. For example, amnesic patients produce fewer associates, semantic features and senses when presented with familiar target words, suggesting that the hippocampus has a role to play in the updating and maintenance of semantic representations (Klooster & Duff, 2015).

Whilst the episodic context account was initially developed to explain word-meaning priming effects with homonyms and the supporting role of sleep, context-specific representations could in principle develop for any linguistic episode (Gaskell et al., 2019; Mak et al., 2024), and hence may not be exclusive to the processing of homonyms. Recent work has supported this notion. In Curtis et al. (2022), word-meaning priming was observed with non-homonymic nouns (defined as nouns with a single entry in the Wordsmyth online dictionary, e.g., *balloon*), indexed by a tendency for non-homonyms to be interpreted in a manner that was consistent with a previous sentence context (e.g., "The entertainer filled the balloon from the gas cylinder and inhaled it to make her voice squeaky") which biased the interpretation of the word towards a particular aspect of meaning (e.g., the sentence is more likely to prime *helium* as opposed to *float*). In Mak et al. (2023), word-meaning priming with non-homonyms was maintained following a 12-hour interval including sleep relative to an equivalent amount of wakefulness, providing further support for the role of sleep in preserving these effects. In a separate experiment, Mak and colleagues examined priming in word-class ambiguous words, defined as words that may serve as either a noun or a verb depending on the context in which it is used (e.g., *loan*). These words were primed towards their dispreferred word class in exposure. For example, the word *loan* is most frequently used as a noun, and was therefore used as a verb in exposure (e.g., "He will loan me some money"). Both 20 min and 12 h later, participants were more likely to use these words in their dispreferred word class, compared to words that were not primed. Concerning the 12-hour delay, this *word-class priming effect* was stronger in the sleep compared to the wake condition.

To summarise, research has shown that lexical processing is influenced by recent linguistic episodes, as indexed by word-meaning and word-class priming. The relative longevity of these effects suggests that the underlying mechanism(s) appear to be independent from transient residual activation processes. Instead, initial accounts of word-meaning priming argued that the increased accessibility of recently encountered meanings was a result of learning processes within the semantic system (Gilbert et al., 2018; Rodd et al., 2016). However, because priming appears to be maintained by sleep-related consolidation (Gaskell et al., 2019; Mak et al., 2023), later studies have implicated a role for episodic memory. This suggests an important interface exists between memory and language, in which stored knowledge of recent linguistic experiences is able to contribute to online language processing in the future. The goal of the present research is to investigate whether these same memory processes play a similar role in supporting online syntactic processing. Specifically, we exploited some of the methods of the word-meaning priming literature to address issues of longevity and memory basis for priming in relation to syntactic interpretation of specific verbs (Ryskin et al., 2017).

In an online pilot experiment that can be found online in a supplementary file (https://osf.io/wj3da/), we initially investigated our research questions using a modified version of the visual-world paradigm based on the work of Ryskin et al. (2017), but focused exclusively on mouse clicking behaviour. Unlike Ryskin and colleagues, however, we did not observe a verb-bias priming effect in this initial experiment. More detailed information relating to the method and results of this experiment can be found in the online supplementary file. Given the findings of this pilot experiment, we decided to examine priming in a simpler paradigm adapted from the work of Branigan et al. (2005). This paradigm made use of a two-alternative forced choice task to measure syntactic interpretation. In Branigan et al. (2005), on a single trial, participants read an ambiguous sentence (e.g., "The policeman prodding the doctor with the gun") and were then presented with two visual scenes, one that illustrated the modifier interpretation (the doctor in possession of the gun, who was being prodded by the policeman) whilst the other illustrated the instrument interpretation (the policeman was using the gun to prod the doctor). Participants were asked to indicate the 'correct' picture for the sentence. Thus, in this paradigm, two visual scenes are presented to the participant, and their choice of scene corresponds to how they may have interpreted the sentence.

We adopted this forced-choice paradigm in our subsequent experiments. In Experiment 1, we tested the sensitivity of this paradigm in detecting an effect of pre-existing verb bias on the resolution of syntactic ambiguities. Twenty-four verbs were classified as having either a pre-existing instrument or pre-existing modifier bias based on Ryskin et al. (2017) and were encountered in syntactically ambiguous contexts. Experiment 2 was a priming study in which half of the 24 verbs were encountered in their dispreferred syntactic interpretation in an exposure phase. The effect of this exposure was tested ~ 20 min later in a separate test phase, where primed and unprimed verbs were encountered in syntactically ambiguous contexts. The key question for Experiment 2 was whether verb-bias priming can be found across intervals of around 20 min, as has been seen repeatedly for word-meaning priming. Experiment 3 went one step further, to test whether verb-bias priming can be found when exposure and test phases are separated by a ~ 12-hour interval that included a period of overnight sleep. The final experiment, Experiment 4, did not manipulate priming but instead measured the strength of verb-specific, pre-existing biases towards the instrument/modifier interpretation using a sentence completion task. As we discuss in more detail later, we performed this experiment to investigate whether differences in pre-existing bias strength could explain discrepancies in verb-bias priming between the instrument and modifier-biased verbs in Experiments 2 and 3.

Experiment 1

Experiment 1 investigated the sensitivity of Branigan et al.'s (2005)

[1] The episodic context account was initially dubbed the *contextual binding account* (Gaskell et al., 2019), but was later changed to the episodic context account in Curtis et al. (2022) to avoid confusion with Yonelinas et al. (2019).

forced-choice paradigm in detecting an effect of pre-existing verb bias. That is, in the absence of any prior priming, is the instrument interpretation of an ambiguous sentence selected more frequently for verbs that are classified as having a pre-existing instrument bias compared to verbs with a pre-existing modifier bias?

Experiment 1, including its predictions, exclusionary criteria and analysis plan, was pre-registered ahead of data collection (https://aspredicted.org/633s-28qb.pdf). We predicted that participants would select the instrument interpretation more frequently when processing verbs with a pre-existing instrument bias, compared to verbs with a pre-existing modifier bias.

Methods

Participants

Twenty-four participants (16 females) took part in Experiment 1 (*M age* = 22.6; *SD age* = 1.58). We aimed for this target sample size following Experiment 1 of Ryskin et al. (2017), who observed an effect of pre-existing verb bias on resolving syntactic ambiguities with 24 participants. Participants were recruited from Prolific (https://www.Prolific.com) and received £1.85 for their participation (~£10/hour). Participants were based in the UK who reported English to be their first language, had normal or corrected-to-normal vision, and reported no known language, attentional, or sleep-related disorders. For all experiments reported in this article, participants provided informed consent prior to participation. This research was approved by the Research Ethics Committee of the Department of Psychology, University of York.

Materials

Verbs were classified as having a pre-existing instrument or pre-existing modifier bias based on the proportion of instrument interpretations they elicited in Ryskin et al. (2017; Experiment 1).[2] The 12 verbs that elicited the instrument interpretation most frequently were classified as having a pre-existing instrument bias (e.g., *hit*), and the 12 verbs that elicited the fewest instrument interpretation were classified as having a pre-existing modifier bias (e.g., *chose*; see Appendix A for a full list of verbs).

The experiment also made use of 48 colour images of objects/instruments (e.g., a stick, a crayon) and 48 images of animals (e.g., a dog, a lion). The animal images were taken from the C.A.R.E stimulus set of normed animal images (Russo et al., 2018), and when not available, were taken from an internet image search. All instrument images were taken from internet image searches. Each instrument image was randomly paired with one of the animal images, which were then incorporated together into a visual scene (see Fig. 1).

From these verbs and images, we then created sentences in the form of "The man/woman **verbed** the **animal** with the **instrument**". Verbs and instrument images were paired together such that a given instrument could plausibly be used to act out the action of the verb. For example, for the verb *hit* that was paired with images of a polar bear and a lamp, we constructed the sentence "The man/woman **hit** the **polar bear** with the **lamp**".

For each sentence, a visual scene depicting the instrument interpretation and a visual scene depicting the modifier interpretation were created. All visual scenes were created to a 315 x 910 rectangular template and presented the animal and instrument contained in the sentence. We discuss the makeup of these two scene types in more detail below.

Instrument scenes (see Fig. 1 – top row of 'Visual scenes'): Instrument scenes presented the target animal towards the left hand side of the scene. Towards the right hand side of the scene, there was an image of a human hand in possession of the target instrument. In total, eight 'instrument hands' were selected (4 male and 4 female). Finally, in the middle of the scene was an arrow, pointing towards the direction of the animal from the hand/instrument. This was intended to illustrate the movement of the hand/instrument towards the animal.

Modifier scenes (see Fig. 1 – bottom row of 'Visual scenes'): Modifier scenes presented the target animal in possession of the target instrument towards the left hand side of the scene. Towards the right-hand side of the scene was an image of a single hand.[3] In the middle of the scene was an arrow intended to illustrate the movement of the hand towards the animal. The hand depicted a pose/gesture that is required to act out the verb contained within the preceding sentence. For instance, the verb *hit* was paired with the image of a hand with a clenched fist, depicting a hitting action. In total, eight unique hand gestures were selected to depict our 24 critical verbs. Hence, some hand gestures (e.g., a hand that is pointing) represented more than one critical verb (e.g., the verbs *poked*, *looked at, found, picked out, spotted, chose, located, pointed to*, and *selected* were all represented by a pointing hand). Four different images (2 male, 2 female) were selected per gesture and sourced from various stock databases.

In addition to our 24 critical verbs, 12 additional verbs were used in filler trials, along with 48 filler animals and 48 filler instruments that did not overlap with animals/instruments on critical trials. The interpretation of the sentence on filler trials was always unambiguous, given the two visual scenes. For instance, given the phrase "The woman scratched the octopus with the nail file", a modifier and instrument scene were presented, but crucially, only one of these scenes contained the animal and instrument that were contained in the sentence (e.g., the image of an octopus and the image of a nail file, that is either possessed by the octopus or by the instrument hand).

Design

Experiment 1 had a within-subjects design with one independent variable (pre-existing verb bias) giving rise to two conditions: verbs with a pre-existing modifier bias and verbs with a pre-existing instrument bias.

The binary dependent variable reflected the selected scene/interpretation on a given trial (1 = the instrument scene was selected; 0 = the modifier scene was selected). In addition, we also measured response time, and we refer the reader to an online supplementary file (https://osf.io/wj3da/) to view an exploratory analysis of the response time data.

Procedure

The experiment was programmed and administered in Gorilla Experiment Builder (https://gorilla.sc/; Anwyl-Irvine et al., 2020). Participants were required to complete the experiment on a desktop or laptop computer, and were asked to complete the experiment in a quiet location with minimal distractions. Note that these instructions were given for all experiments reported in this article.

Before beginning the experiment, participants received instructions on how to complete the experiment. They were told that on any given trial, they would first be presented with a written sentence, which they were asked to read carefully. Next, two visual scenes would appear. Participants were instructed to select the scene that they believed best corresponded to the previous sentence, and to do so as quickly and as accurately as possible.

[2] We classified our verbs in a different way to Ryskin et al. (2017), who classified their verbs based on a norming study, conducted before their Experiment 1. Thus, some verbs are classified into different categories across studies. We decided to classify verbs based on the visual-world paradigm data of Experiment 1 in Ryskin et al. (rather than their norming study) as we originally conducted a similar visual-world paradigm and therefore felt that this data provided a more relevant measure of bias than the norming study which used a sentence completion task.

[3] The exception to this is the verb *hugged*, which was represented by two hands facing towards the animal, depicting a hugging gesture. We felt this was necessary to depict *hug* accurately, which was difficult to achieve with just a single hand. When we inspected verb-specific performance in the experiments reported in this article, *hugged* did not show atypical behaviour relative to other modifier-biased verbs in any experiment.

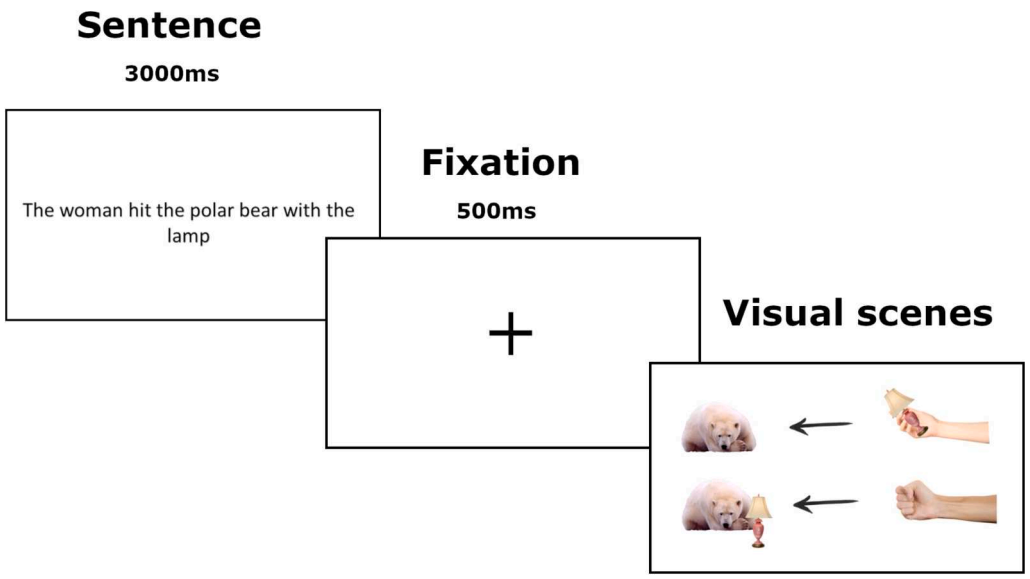

Fig. 1. Illustration of trial progression in Experiment 1.

The experiment then began with four filler 'practice' trials (the same 4 trials were used across participants). The remainder of the experiment then consisted of the 48 critical trials (2 trials per verb) and the 44 remaining filler trials (4 trials per verb, although 4 of these trials appeared as the practice trials). Trial order was randomised across participants.

On any given trial, a written sentence appeared at the centre of the screen for 3000 ms. This was then followed by a fixation cross for 500 ms, which was replaced by the two visual scenes in the top and bottom halves of the screens. The position of the modifier and instrument scenes to these respective locations was counterbalanced within participants, such that each interpretation appeared in the respective halves an equal number of times. If the participant believed that the top scene provided the best correspondence to the sentence, they were instructed to press the 't' key on the keyboard, whilst the 'b' key was selected for the bottom scene. Participants could make their decision as soon as the two scenes appeared. Following their response, a written prompt then appeared asking the participant to press Spacebar to move onto the next trial. The whole experiment took approximately 10 min to complete.

Analysis approach

The data from all of the experiments reported in this article was analysed using generalised mixed-effects modelling in *RStudio* (version 4.0.4; R Core Team, 2021) using the *lme4* package (Bates et al., 2015). All (categorical) fixed effects were sum-coded. To construct our random-effects structures, we used the *Buildmer* package (Voeten, 2022), which allows users to submit the most complex random-effects structure that is justified by the design of the experiment (Barr et al., 2013). From this maximal model, Buildmer can determine the most maximal model that is capable of converging, such that information rich effects are included in the model. The 'Bobyqa' optimizer was used to increase the likelihood of model convergence. The direction argument was set to 'order'[4] to avoid elimination of fixed effects. Note that this model building procedure is used across all experiments reported in this paper.

Results

The instrument interpretation was selected more frequently for verbs with a pre-existing instrument bias (*Minstrument interpretation* = .73, *SD* = .44) compared to verbs with a pre-existing modifier bias (*Minstrument interpretation* = .51, *SD* = .50; see Fig. 2). Indeed, the results from our model revealed there to be a statistically significant effect of pre-existing verb bias. ($B = 0.62$, $SE = 0.15$, $z = 4.17$, $p < .001$).

Discussion

Experiment 1 served to evaluate the sensitivity of Branigan et al.'s (2005) forced-choice paradigm in detecting an effect of pre-existing verb bias on resolving syntactic ambiguities, in the absence of any prior priming. As predicted, we observed a significant effect of verb bias: The instrument interpretation was selected significantly more frequently following verbs with a pre-existing instrument bias relative to verbs with a pre-existing modifier bias.

An unexpected observation was the high proportion of instrument interpretations in the modifier-biased condition (0.51). For comparison, the proportion of trials eliciting the instrument interpretation in response to a modifier-biased verb was 0.19 for the same verbs in Ryskin et al. (2017; Experiment 1). This difference could relate to our decision to pair verbs with semantically plausible objects (e.g., the verb *looked (at)* was paired with *telescope*) which was not done in Ryskin et al. (2017), meaning that the instrument interpretation was likely perceived as globally more viable in our experiment. We return to this point later in General Discussion.

Nonetheless, having confirmed the suitability of the forced-choice task for detecting an effect of verb bias, Experiment 2 investigated the effect of prior exposure on subsequent syntactic ambiguity after a delay of roughly 20 min.

Experiment 2

Unlike Ryskin et al. (2017), which used prime and test sentences intermixed within a single session, Experiment 2 was split into two phases: an exposure and a test phase. During the exposure phase, we attempted to bias the interpretation of verbs with a pre-existing modifier bias towards an instrument interpretation and vice versa. Verbs were

[4] In our pre-registration, we incorrectly stated that we would use Buildmer to identify our random-effects structure via backward stepwise elimination of effects based on changes to log-likelihood (by setting the direction argument to 'backward'). This method, however, risks the removal of fixed effects, including interaction terms. Since the examination of the interaction between pre-existing verb bias and priming is critical for our predictions in Experiment 2 and Experiment 3, we decided to deviate slightly from this pre-registered method to ensure the survival of our full fixed-effects structure, for all experiments reported in this paper. Accordingly, we set the direction argument to 'order' so that Buildmer instead identified the most maximal random-effects structure that is capable of converging.

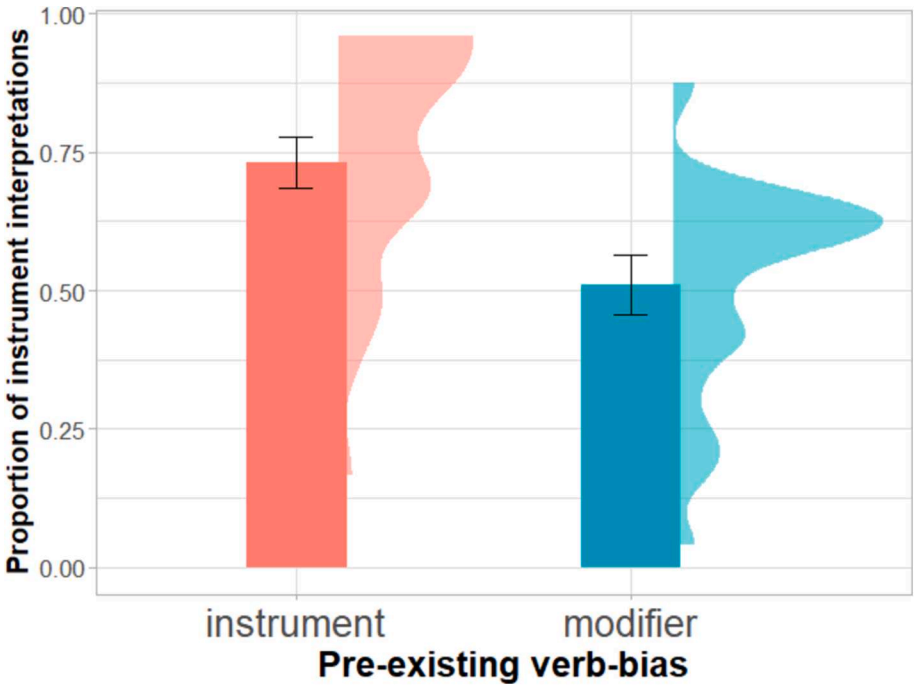

Fig. 2. Mean proportion of instrument interpretations across verb bias conditions in Experiment 1. Error bars represent 95% within-subject confidence intervals (Morey, 2008). Density functions represent participant mean scores for each condition, generated with a bounded density estimator using the reflection method.

therefore encountered in their dispreferred interpretations in the exposure phase. This was achieved by presenting a visual scene in a way that was consistent with the dispreferred interpretation. For example, for the sentence "The man hit the butterfly with the book", a visual scene depicting a butterfly in possession of a book (see Fig. 3), was presented, unambiguously biasing the modifier interpretation of the verb. Note that our method of biasing verbs towards their dispreferred interpretation differs from Ryskin et al. (2017) who used equi-biased verbs that were primed towards either one of the two interpretations in different conditions. Part of the reason for priming towards dispreferred interpretations was that word-meaning priming effects tend to be larger when the subordinate (dispreferred) meaning is primed (Curtis et al., 2022; Rodd et al., 2013).

The test phase used the same stimuli and parameters as Experiment 1. Crucially, however, the test phase of Experiment 2 was preceded by both an exposure phase, in which 12 verbs were primed towards their dispreferred interpretations, and a ~ 10-minute filler task. This allowed us to investigate the effect of prior exposure on subsequent interpretations involving the same verb, with an approximate lag of 20 min from the final presentation of a given verb in the exposure phase to it being re-encountered in the test phase. Furthermore, the introduction of the filler task induced a relatively long delay between the

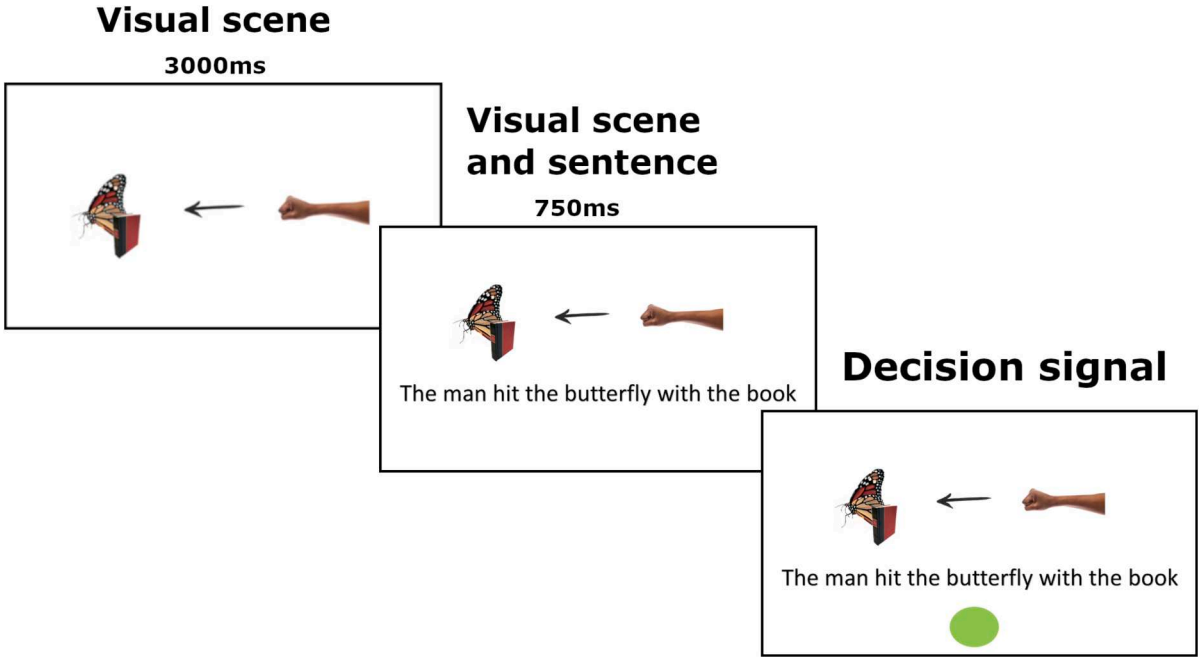

Fig. 3. Illustration of trial progression in the exposure phase of Experiment 2.

presentation of (primed) verbs across tasks. Hence, residual activation mechanisms (e.g., Pickering & Branigan, 1998) should not survive this interval and therefore should have little effect on verb processing.

Experiment 2, including its predictions, exclusionary criteria and analysis plan, was pre-registered ahead of data collection (https://aspredicted.org/szxm-svzd.pdf). We made the following predictions:

1. For verbs that receive no prior priming in the exposure phase, we predicted participants will be more likely to select the instrument interpretation for verbs with a pre-existing instrument bias than a modifier bias.
2. In the priming condition – where verbs are primed towards their dispreferred interpretation – we predict that this difference will be reduced or even reversed. As a result, we predicted a priming by pre-existing verb bias interaction. In other words, primed verbs will be more likely to elicit the dispreferred interpretation than the unprimed condition. To explore this, we pre-registered that we would examine the simple effect of priming within each verb bias condition.

Methods

Participants

Sixty participants (32 females) took part in Experiment 2 (*M age* = 22.42; *SD age* = 1.93). Participants were recruited from Prolific and received £6.50 for their participation (approximately £10/hour). Participants were based in the UK who reported English to be their first language, had normal or corrected-to-normal vision, and reported no known language, attentional, or sleep-related disorders.

As pre-registered, our sample size of 60 participants was based on Experiment 2 of Ryskin et al., (2017), who observed an effect of priming on resolving syntactic ambiguities with 60 participants.

Materials

The test phase of Experiment 2 made use of the same visual scenes that were used in Experiment 1. For the exposure phase, unique images were used, with the intention of minimising the possibility of participants developing associations between a particular image and a certain interpretation in the exposure phase, which could have influenced behaviour in the test phase. Thus, the exposure phase made use of 48 images of instruments/objects that did not overlap with the instruments/objects used in the test phase, and we selected 48 *different* images of the animals used in the test phase. In addition, 48 filler trials (24 instrument scenes and 24 modifier scenes) were created to appear in the exposure phase. These trials involved the same 48 filler animals as used in the test phase, but with a unique set of images. Forty-eight unique additional instruments were also selected to serve in the filler trials of the exposure phase. Finally, unique hand images appeared in the exposure and test phases.

Design

Experiment 2 had a within-subjects design with the independent variables *Pre-existing verb bias* (modifier vs. instrument), and *Priming* (primed vs. unprimed).

For a given participant, 12 verbs appeared in the primed condition (6 per verb bias condition) and 12 in the unprimed condition. Whether a verb appeared in the primed or unprimed condition was counterbalanced across participants.

Our dependent variable follows on from Experiment 1. Namely, we measured the selected interpretation as a binary variable.

Procedure

Experiment 2 began with the exposure phase. On any given trial, participants viewed a single visual scene. After 3000 ms, a sentence in the form of 'The man/woman **verbed** the **animal** with the **instrument**' was presented below (see Fig. 3). Participants were tasked with deciding whether the sentences described the visual scene. They pressed the 'y' key on their keyboard if they believed the sentence described the visual scene, or the 'n' key if they believed the sentence did not describe the visual scene.

On critical trials (trials where a critical verb was primed towards its dispreferred interpretation) the sentence always matched and described the visual scene. Crucially, however, the scene depicted the verb being used in its dispreferred manner. For instance, for instrument-biased verbs, the visual scene depicted a modifier interpretation, where the animal is in possession of the instrument. For modifier-biased verbs, an instrument interpretation of the sentence was presented. In total, there were 48 critical trials, with 4 trials per verb.

Presenting the scene before the sentence in the exposure phase was an important component of the trial structure. If the sentence was presented first, we reasoned that the participant may create a mental image of the sentence, which would likely adhere to the verb's dominant interpretation. The visually presented scene, where the verb is used in its dispreferred manner, would then be incongruous to the mental image. In this case, the participant might be less likely to accept the match between the sentence and visual scene which could discourage priming. On the other hand, by presenting the sentence after the scene, we hoped this would increase the perceived correspondence between the scene and sentence. Indeed, on critical trials, the scenes and sentences always matched, albeit with the scene depicting the verb in its dispreferred usage.

Forty-eight filler trials that did not involve any of the primed critical verbs were included in the exposure phase. In order to encourage sentential and verb processing, and to discourage participants from comparing the sentence and visual scene superficially based on the animal and instrument, we included 24 filler trials where the sentence did not describe the visual scene, based on the verb presented in the sentence. For instance, based on Fig. 3, the filler sentence might read "The man kicked the butterfly with the book". Here, the verb kick is seemingly not plausible since only an actor's hand with a clenched fist, rather than an actor's foot, is present and is being used to interact with the animal. In total, seven filler verbs (3 trials per verb) that denote actions performed without the use of a hand/arm were selected to serve in these filler trials. Through requiring participants to base their decision around the plausibility of the verb given the visual scene, it was hoped that this would encourage participants to process the sentence and verb more thoroughly (and hence encourage priming of the verb). Each "non-hand/arm" filler verb was presented three times, giving rise to 21 filler trials of this type in total.

In addition, and to include some variability concerning how the mismatch between the sentence and scene was portrayed, 24 further filler trials were included where the sentence did not describe the visual scene based on the animal or instrument contained in the sentence. These particular trials recruited seven more additional verbs that did not overlap with existing critical or filler verbs. For example, based on Fig. 3, the sentence might read "The man identified the butterfly with the ladder", which causes a mismatch since in the visual image the butterfly is in possession of a book, not a ladder.

Participants could make their decision 750 ms after the onset of the sentence. This delay was included to encourage the participant to scrutinise the scene and sentence as closely as possible before responding. The end of the delay period was signalled by a green circle which appeared below the sentence, signalling to the participant that they may respond. If a participant responded correctly, 'Correct!' in green font appeared above the sentence for 500 ms. If the response was incorrect, 'Incorrect!' appeared in red font, also for 500 ms. Following this, participants were instructed to press the spacebar to advance to the next trial. The exposure phase was made up of 96 trials (48 critical and 48 filler trials), with the presentation order randomised across participants.

After the exposure phase, participants completed a filler task where they watched a 10-minute video of Shaun the Sheep that was chosen for

its minimal linguistic content. Following the video, participants answered three questions related to the video to ensure they were paying attention (all participants answered at least 2 of the 3 questions correctly). Afterwards, participants completed the test phase, which consisted of the same stimuli and parameters as Experiment 1. With the inclusion of the filler task, the median lag between the final presentation of a given verb in the exposure phase and the first presentation of the same verb in the test phase was 18.55 min ($IQR = \pm$ 5.58 min). The whole experiment took approximately 30 min to complete.

Results

The mean proportions of instrument interpretations for each condition are summarised in Fig. 4, and the output from our statistical model is presented in Table 1. It is worth pointing out here the predicted direction of results for each verb bias condition. Concerning the instrument-biased verbs, the primed condition was expected to elicit fewer instrument interpretations than the unprimed condition since verbs in the primed condition were exposed to the modifier interpretation in the exposure phase. The opposite is true for the modifier-biased verbs: verbs in the primed condition were expected to elicit more instrument interpretations than the unprimed condition since verbs in the primed condition were exposed to the instrument interpretation in the exposure phase.

Overall, there were no significant main effects of pre-existing verb bias ($p = .149$) or priming condition ($p = .597$). We now turn to discussing the results in relation to our predictions. To test our first prediction that unprimed instrument-biased verbs would select the instrument interpretation more frequently than unprimed modifier-biased verbs, we employed the emmeans package (Lenth, 2021), as pre-registered, to statistically compare the two conditions. This comparison revealed a statistically significant difference ($B = 0.65$, $SE = 0.32$, $z = 2.03$, $p = .043$), with the instrument interpretation selected more frequently following verbs with a pre-existing instrument bias ($M_{instrument\ interpretation} = .53$, $SD = .50$) compared to verbs with a pre-existing modifier bias ($M_{instrument\ interpretation} = .43$, $SD = .49$). This supports our first hypothesis that pre-existing verb bias, in the unprimed condition, influenced syntactic interpretation.

Our second prediction was confirmed by a significant interaction between pre-existing verb bias and priming ($p = .021$). To follow up the interaction, we used the emmeans package to examine the simple effect of priming within verb bias conditions. For the instrument-biased verbs, the instrument interpretation was selected significantly less frequently ($B = -0.32$, $SE = 0.16$, $z = -2.00$, $p = .046$) in the primed ($M = .48$, $SD = .50$) than the unprimed condition ($M = .53$, $SD = .50$). For the modifier-biased verbs, while the primed condition elicited the instrument interpretation more frequently ($M = .46$, $SD = .50$) than the unprimed condition ($M = .43$, $SD = .49$), this difference was not statistically significant ($B = 0.20$, $SE = 0.16$, $z = 1.28$, $p = .202$). These results suggest that a verb-bias priming effect was present, particularly in relation to the instrument-biased verbs.

Table 1
Summary of fixed effect terms in Experiment 2.

	Estimate (*B*)	SE	z	p
Intercept	−1.33	0.21	0.63	.527
Pre-existing verb bias	0.19	0.13	1.44	.149
Priming	−0.03	0.06	−0.53	.597
Pre-existing verb bias x Priming	−0.13	0.06	−2.32	.021*

Note: * Statistically significant effect at alpha < .05. Model was configured over 2880 observations, comprising 60 subjects and 24 verbs.

Discussion

In line with our first hypothesis, syntactic ambiguity resolution in the unprimed condition was influenced by pre-existing verb biases, indicating that pre-existing verb biases influence online syntactic processing (Boland et al., 1995; Ryskin et al., 2017; Snedeker & Trueswell, 2004; Trueswell et al., 1993). In line with our second prediction, we found an interaction between priming and pre-existing verb bias, suggesting a verb-bias priming effect (Ryskin et al., 2017). When we examined priming separately for each verb bias condition, we found that when the instrument-biased verbs were encountered in their dispreferred (modifier) interpretation in the exposure phase, the modifier interpretation was significantly more likely to be recruited ~ 20 min later, compared to the unprimed condition (the proportion of trials to use the modifier interpretation increased by .05). In contrast, however, we observed no

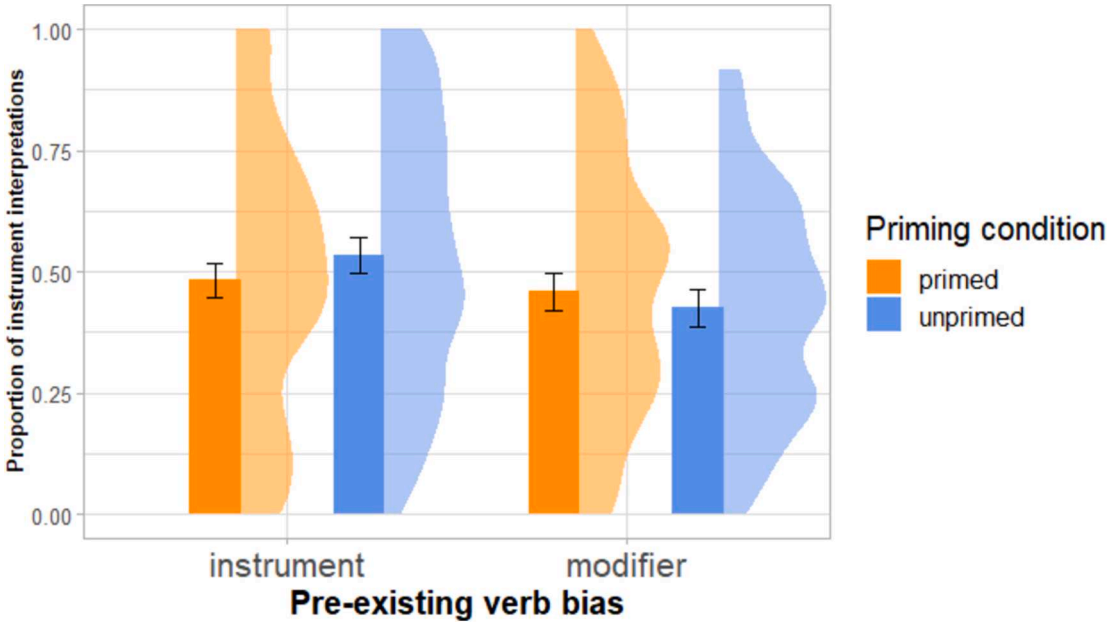

Fig. 4. Mean proportion of instrument interpretations in the test phase of Experiment 2. Verbs in the primed condition were presented in their dispreferred interpretation in the exposure phase. Error bars represent 95% within-subject confidence intervals. Density functions represent participant mean scores for each condition, generated with a bounded density estimator using the reflection method.

significant priming effect in relation to the modifier-biased verbs (.03 difference in the proportion of trials to use the instrument interpretation).

These results extend previous findings of verb bias malleability in two ways. In Ryskin et al. (2017), priming was observed when prime and test trials were intermixed in the same experimental block and separated by a median lag of 6 trials, and was observed for equi-biased verbs which do not have a strong bias towards a particular syntactic interpretation. Here, however, we showed that verb-bias priming is observed when prime and test trials are separated by a ~ 20-minute interval. We also showed that it is possible to prime dispreferred syntactic interpretations of specific verbs. However, these findings were only found in relation to the instrument-biased verbs.

The main theoretical contribution of this result relates to the issue of longevity. For previous studies of verb-bias priming, it was hard to definitively rule out a residual activation interpretation of the results, given that effects were within-session and with a median of 6 intervening trials between prime and test sentences. Here, the effect was found between sessions, and with an interval between prime and test sentences of roughly 20 min. This is beyond the range of lag that could be explained in terms of the residual activation of nodes in a spreading activation or similar network, and so we can be confident that that the shifts in verb bias that we see fall in the domain of learning and memory, similar to effects seen in the word-priming literature (e.g., Rodd et al., 2016).

Intriguingly, pre-existing verb bias appeared to play a weaker role in resolving syntactic ambiguities compared to Experiment 1. In Experiment 1, for example, the proportion of instrument interpretations elicited by instrument-biased verbs was 0.73, compared to 0.51 for modifier-biased verbs. This equates to a difference score of 0.22. In the unprimed conditions of Experiment 2, however, this difference decreased, with a difference score of 0.10. It is possible, therefore, that whilst our design aimed to prime specific verbs, there is perhaps some 'spillover' effect occurring such that participants seem to rely less on their pre-existing verb knowledge, even when processing the unprimed control verbs. Tentatively, if episodic memory is playing some role in the observed verb-bias priming, then this spillover effect could relate to the proposed (un)specificity of context-specific representations. The episodic context account postulates that context-specific representations may encode a 'gist-like' representation of a linguistic episode, as opposed to more crisp and fine details pertaining to specific words (Curtis et al., 2022; Gaskell et al., 2019; Mak et al., 2023; 2024). A consequence of this is that the application of encoded knowledge could be quite flexible and may extend to other and similar lexical items. In line with this, Curtis et al. (2022) found that replacing the target word (e.g., *balloon*) with a semantically related word at test (e.g., *vessel*) still led to priming of the probe word (*helium*), despite *vessel* not appearing in the exposure phase. A similar process could have occurred in Experiment 2. That is, encountering *smacked* in the exposure phase may not only have influenced how this same verb is later processed, but also the (unprimed) verbs *hit* and *whacked* which have similar meanings. Another possibility is that participants acquired a general understanding that in the context of the experiment, pre-existing verb knowledge is not as important in resolving syntactic ambiguities as it might otherwise be, to the extent that it is suppressed. This understanding could have been acquired in the exposure phase, where verbs were encountered in a manner that was inconsistent with pre-existing knowledge (see also Clayards et al., 2021 for similar experiment-specific learning).

In sum, the results of Experiment 2 showed that verb-bias priming is maintained ~ 20 min after exposure to primed information, suggesting that it is a memory effect rather than a residual activation effect. Such an effect is predicted by a broader episodic context account of language comprehension (Gaskell et al., 2019), which also predicts that verb-bias priming should be preserved over a longer period, provided a period of sleep is incorporated (Gaskell et al., 2019; Mak et al., 2023). In Experiment 3, therefore, we further addressed the issue of longevity by measuring the maintenance of priming over a period of ~ 12 h across sleep.

Experiment 3

One way to probe the role of sleep-related consolidation would be to compare verb-bias priming between a group of participants who slept soon after the exposure phase with a group of participants who spent an equivalent amount of time awake. To explore the feasibility of this option, we ran a series of power analyses in which we simulated data for the wake condition (DeBruine & Barr, 2021). We specifically constrained the simulated data such that the magnitude of the priming x pre-existing verb bias interaction was half that of Experiment 2, following the assumption that priming would diminish over a 12-hour interval of wake due to a lack of a consolidation effect on episodic memory. These analyses revealed that 400 participants *per* delay group would only provide ~ 65 % statistical power for detecting a 3-way interaction between priming, pre-existing verb bias, and delay group. Hence, we decided to pursue the more modest goal (at least initially) of testing whether a simple effect of priming could be observed after a 12-hour period including sleep, while leaving open the possibility of exploring a wake condition in a future experiment.

Experiment 3, including its predictions, exclusionary criteria and analysis plan, was pre-registered ahead of data collection (https://aspredicted.org/6jdg-b4vb.pdf). Participants completed the exposure phase of the experiment some time between 8:30——10:30 pm in the evening (Session 1), and completed the test phase the following morning, some time between 8:30——10:30 am (Session 2). If episodic memory supports verb-bias priming via the formation of context-specific representations, then we reasoned that priming would be maintained following the ~ 12-hour interval, due to sleep-related consolidation of contextual information. Accordingly, we made the following predictions:

1. For verbs that receive no prior priming (during the exposure phase), we predicted that participants will be more likely to select the instrument interpretation for verbs with a pre-existing instrument bias than a modifier bias.
2. In the priming condition – where verbs are primed towards their dispreferred interpretation – we predicted that this difference will be reduced or even reversed. As a result, we predict a priming by pre-existing verb bias interaction. In other words, primed verbs will be more likely to elicit the dispreferred interpretation than the unprimed condition. To explore this, we pre-registered that we would examine the simple effect of priming within each verb bias condition.

Methods

Participants

Potential participants were initially recruited on Prolific who completed a screening survey. Respondents provided demographic information, read details of the main experiment, and indicated their preference for taking part. This recruiting method has been used in previous online sleep studies (see Mak, 2024 for procedural details).

In total, 307 respondents completed the survey, of which 242 indicated that they would like to take part in the main experiment. From this initial sample, 16 respondents were excluded from participating for the following reasons: reporting to have a developmental, attentional, language or sleep disorder (n = 13); reporting to have an age other than 18——25 years (n = 2); reporting English not to be their native language (n = 1). From the 226 eligible participants, 139 completed both sessions of the experiment (70 participants did not complete either session; 17 participants completed Session 1 without completing Session 2). Of the 139 participants who completed both sessions, 28 were excluded from statistical analysis for meeting the following pre-registered exclusion

criteria: providing a score of six or more on the Stanford Sleepiness Scale in Session 1 (n = 7) or Session 2 (n = 1); slept for less than six hours between the exposure and test phase (n = 4); stating that their overnight sleep quality was 'poor' or 'very poor' (n = 9); and a further seven participants were excluded for meeting two or more of these criteria. The final sample thus consisted of 111 participants (67 females; *M age* = 22.78; *SD age* = 1.90), slightly overshooting our pre-registered target sample size of 106–110 participants. Our target sample size was derived by performing simulations with the objective of reaching 80 % power to observe the pre-existing verb bias x priming interaction observed in Experiment 2. Power simulations were conducted in *RStudio* using the *simr* package (Green & MacLeod, 2016). All participants were based in the UK who reported English to be their first language, had normal or corrected-to-normal vision, and reported no known language, attentional, or sleep-related disorders. Completion of both experimental stages resulted in a payment of £4.20 (approximately £10/hour).

Materials

Experiment 3 made use of the same materials as those in Experiment 2.

Design

Experiment 3 was identical to Experiment 2, except the delay between the exposure and test phases was extended from 20 min to 12 h. Further, the filler task of Experiment 2 was omitted in Experiment 3, with participants instead free to go about their daily life.

Procedure

Experiment 3 consisted of two experimental sessions. Participants began Session 1 between 8:30 pm and 10:30 pm, and returned to begin Session 2 some time between 8:30 am and 10:30 am the following morning. In total, the two sessions took approximately 25 min to complete.

Session 1: Session 1 began with two measures of alertness. First, participants judged their subjective level of sleepiness by completing the Stanford Sleepiness Scale (SSS; Hoddes et al., 1973). Second, participants completed a simple reaction time task to provide an objective measure of alertness. Following this, participants completed the exposure phase of the experiment, in which 12 verbs were primed towards their dispreferred interpretation. The materials and procedures of the exposure phase were identical to the exposure phase of Experiment 2.

Session 2: Upon beginning Session 2, participants provided a second SSS rating. They then completed a reduced version of the Morning/Eveningness questionnaire (rMEQ; Adan & Almirall, 1991), which assessed circadian preferences. Here, participants were also asked to report their perceived overnight sleep duration and quality. This was followed by a simple reaction time task, which was followed by the test phase of the experiment. The materials and procedures of the test phase were identical to that of Experiment 2.

Results

Sleep and alertness measures

Before presenting the results from the main analysis, we first present the data related to the sleep and alertness measures. These data are summarised in Table 2.

We performed a paired-samples *t*-test comparing SSS scores across sessions. This revealed a statistically significant difference ($t(110) = 2.62$, $p = .010$), with participants reporting lower subjective levels of sleepiness in Session 2 in the morning compared to Session 1 in the evening. In terms of response time in the simple reaction time task, response times were numerically quicker in Session 2 compared to Session 1, but this did not reach statistical significance ($t(110) = 1.86$, $p = .066$).

Primary analysis

The mean proportion of instrument interpretations for each condition are summarised in Fig. 5, and the output from our statistical model is presented in Table 3.

Overall, there was no significant effect of pre-existing verb bias ($p = .266$) or priming ($p = .139$). As pre-registered, we examined our specific predictions using the emmeans package. Contrary to our first prediction (i.e., unprimed instrument (vs. modifier) verbs eliciting more instrument interpretation) and Experiments 1 and 2, we found no evidence for a pre-existing verb bias effect ($B = 0.42$, $SE = 0.31$, $z = 1.34$, $p = .18$).

In terms of our second prediction, the interaction between pre-existing verb bias and priming was non-significant ($p = .192$). As in Experiment 2, and as pre-registered, we nonetheless assessed the simple effect of priming within verb bias conditions. For instrument-biased verbs, there was a significant ($B = -0.27$, $SE = 0.14$, $z = -1.97$, $p = .049$) difference between the primed (*Minstrument interpretation* = .47, $SD = .50$) and unprimed condition ($M = .52$, $SD = .50$). For modifier-biased verbs, there was no significant difference between priming conditions ($B = -0.02$, $SE = 0.14$, $z = -0.14$, $p = .893$).

Exploratory analysis

This analysis examined the data collectively across Experiments 2 and 3 to explicitly model the effect of length of delay between the exposure and test phase. 'Experiment' was, therefore, included as a between-subjects fixed-effect in a generalised mixed-effects model (sum coded). This analysis revealed that across both experiments combined there was a significant two-way interaction between priming and pre-existing verb bias ($B = -0.10$, $SE = 0.05$, $z = -2.15$, $p = .032$). For the instrument-biased verbs, there were significantly ($p = .037$) fewer instrument interpretations in the primed compared to the unprimed condition, whereas there was no significant difference across priming conditions for the modifier-biased verbs ($p = .483$). This finding complements the individual analyses of Experiment 2 and Experiment 3 where priming was only found for the instrument-biased verbs. Interestingly, there was no significant three-way interaction between priming, pre-existing verb bias, and experiment ($B = -0.03$, $SE = 0.03$, $z = -1.24$, $p = .216$). This suggests that the pattern of priming was similar across experiments. For example, the mean difference between the primed and unprimed conditions for instrument-biased verbs was.05 in both experiments (e.g., see Fig. 4 and Fig. 5). However, it should be noted that the analysis may not have sufficient statistical power to detect a significant three-way interaction and hence cross-experiment differences.

Discussion

In terms of our first prediction, we found a non-significant difference between instrument and modifier-biased verbs in the unprimed condition, implying that pre-existing verb bias knowledge did not have an influential role in resolving syntactic ambiguities. Hence, whatever knowledge was gained in the exposure phase that subsequently subdued the effect of pre-existing verb bias (see discussion of Experiment 2 for potential explanations), clearly remained influential ~ 12 h later. For

Table 2
Mean (standard deviation) SSS and rMEQ scores, and mean (standard deviation) response time in the simple reaction time task.

Measures	Mean (SD)
SSS Session 1	2.80 (1.03)
SSS Session 2	2.46 (1.11)
rMEQ	13.57 (2.54)
Simple RT Session 1 (ms)	407.22 (94.45)
Simple RT Session 2 (ms)	387.35 (91.37)

Notes: SSS scores range from 1 to 6, with higher values indicating greater sleepiness. MEQ scores range from 5 to 25, with higher values indicating greater morningness preferences.

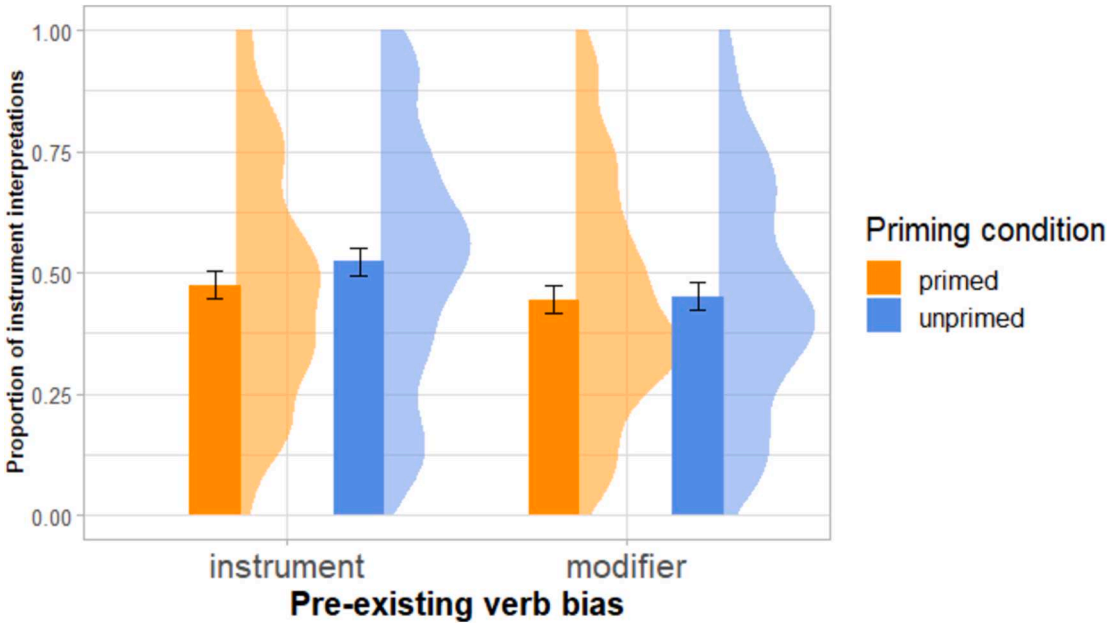

Fig. 5. Mean proportion of instrument interpretations in the test phase of Experiment 3. Verbs in the primed condition were presented in their dispreferred interpretation in the exposure phase. Error bars represent 95% within-subject confidence intervals. Density functions represent participant mean scores for each condition, generated with a bounded density estimator using the reflection method.

Table 3
Summary of fixed effect terms in Experiment 3.

	Estimate (*B*)	Std. error	z	p
Intercept	−0.13	0.15	−0.81	.417
Pre-existing verb bias	0.15	0.13	1.11	.266
Priming	−0.07	0.05	−1.48	.139
Pre-existing verb bias x Priming	−0.06	0.05	−1.31	.192

Note: Model was configured over 5328 observations, comprising 111 subjects and 24 verbs.

our second prediction, there was no significant interaction between priming and pre-existing verb bias, suggesting that prior exposure to the dispreferred syntactic interpretation had a limited role to play when its effect was assessed ~ 12 h later. However, there was a simple effect of priming for the instrument-biased verbs but not for the modifier-biased verbs, mirroring the results from Experiment 2. In line with this, an exploratory analysis which examined the data collectively across Experiments 2 and 3 revealed a significant interaction between priming and pre-existing verb bias, implicating stronger verb-bias priming for instrument-biased verbs.

In sum, there is modest evidence that priming was maintained over a longer time frame, beyond the ~ 20-minute interval of Experiment 2. Given the modest evidence of priming being maintained over a ~ 12-hour interval, we decided not to pursue priming in an equivalent wake condition.

Although we decided against conducting a further priming experiment, there were two unexpected findings which we considered worthy to investigate further. Firstly, why did verbs classified as having a pre-existing modifier bias frequently elicit the instrument interpretation, given their supposed bias for the modifier interpretation? For example, in Experiment 1, the mean proportion of instrument interpretations elicited by modifier-biased verbs was 0.51. This seems relatively high, as we might have expected to observe a lower number, perhaps around 0.25–0.30, to mirror the proportion of 0.73 in the instrument-biased condition. As we have already discussed, this could relate to our method of pairing specific verbs with semantically plausible objects which was not done in prior work (Ryskin et al., 2017), therefore enhancing the plausibility of the instrument interpretation. Another possibility is that the general pre-existing bias for the modifier interpretation was simply quite weak, with some verbs perhaps having a stronger bias towards the instrument interpretation. These two factors need not be mutually exclusive, since a verb may display a stronger bias for the instrument interpretation in the presence of a semantically plausible object that is necessary to perform the instrument interpretation (compared to sentence contexts containing a less plausible object). Secondly, why did we not observe significant verb-bias priming with modifier-biased verbs, and could this be linked to the (potential) weak bias for the modifier interpretation? There are reasons to suspect that this could be the case. Part of this reasoning stems from syntactic priming, where priming effects are enhanced in relation to a word with a relatively strong bias towards a particular syntactic structure (an effect known as the *inverse preference* or *prime surprisal effect*). For example, the production of the double object (DO) construction is more likely after processing a prime DO sentence containing a verb with a relatively strong bias for the prepositional object construction (Bernolet & Hartsuiker, 2010; see also Fine & Jaeger, 2013; Jaeger & Snider, 2013; Peter et al., 2015). Similarly, the magnitude of word-meaning priming is also modulated by the strength of bias towards distinct meanings, with stronger priming for words with a relatively strong bias towards a particular meaning (Curtis et al., 2022; Rodd et al., 2013). Results from these separate literatures thus highlight an important, modulating effect of pre-existing biases on priming in the language domain. In our experiments, then, if the modifier-biased verbs have relatively weak biases compared to their instrument-biased counterparts, then this could provide a partial explanation for why we did not observe priming with these verbs.

Taking all this into account, we decided to conduct Experiment 4,[5] which aimed to establish well-powered (n = 100) estimates of the strength of bias towards the instrument/modifier interpretation on a verb-specific level using a sentence completion task. Here, participants read a series of sentence fragments containing one of our 24 verbs (e.g., "The man bopped/chose the lion with the…") and were asked to provide a sensible and plausible ending. Although Ryskin et al. (2017) conducted

[5] We thank three anonymous reviewers for suggesting this experiment.

a very similar norming study, their sample consisted of US-based participants. We therefore deemed it prudent to run our own experiment with UK-based participants in order to match our samples in Experiments 1–3.

It could be argued that we already have existing data related to pre-existing bias from Experiment 1, in the form of verb-specific instrument interpretations in this experiment. However, we thought that a sentence completion task provided a more natural measure of pre-existing bias since participants had more freedom in how they interpreted and finished the sentence, compared to interpreting a sentence from one of two visual scenes (Experiment 1). The sentence fragments also did not contain an object, meaning there was no influence of object plausibility (with respect to the verb) which we have speculated as a potential reason for the relative preference of the instrument interpretation in our previous experiments. Finally, each verb was processed by 100 participants in Experiment 4, meaning that the resulting, verb-specific estimates are likely to be well-powered and potentially more reliable than Experiment 1 where each verb was processed by 24 participants.

In sum, the data from Experiment 4 were used to compare the strength of verb biases across the instrument and modifier-biased conditions, and were also included in a statistical model exploring the predictive function of bias strength on verb-bias priming in Experiments 2 and 3.

Experiment 4

In Experiment 4, participants read a series of sentence fragments, each one containing one of our 24 verbs (e.g., "The man bopped/chose the lion with the…") and were asked to provide a sensible and plausible ending. Responses could be classified as an instrument continuation (e.g., "stick") or a modifier continuation (e.g., "loudest roar"), and the proportion of instrument continuations for each verb (across participants) was calculated.

Experiment 4 was pre-registered ahead of data collection: https://aspredicted.org/bwh3-gbwz.pdf.

Methods

Participants

One hundred participants (57 females) took part in Experiment 4 (*M age* = 22.42; *SD age* = 1.98). Participants were recruited from Prolific and received £0.90 for their participation (approximately £7/hour). Participants were based in the UK who reported English to be their first language, had normal or corrected-to-normal vision, and reported no known language, attentional, or sleep-related disorders.

We based our sample size on Ryskin et al. (2017), who performed a very similar norming study for establishing a measure of bias strength with this sample size.

Materials

Our materials consisted of a series of sentence fragments containing the *with* prepositional phrase (e.g., "The man hit/chose the lion with the…") used in Ryskin et al. (2017). For each of the 24 verbs, four different sentences were constructed with a different animal on each occasion (the subject of the sentence was "the man" in two sentences and "the woman" in the other two) to remain consistent with the presentation of verbs in Experiments 1–3. The four sentences were placed into 4 experimental lists, with a single list containing all 24 verbs and an equal proportion of man/woman sentences. Each participant encountered sentences from a single list, meaning each verb was processed by a single participant once. An additional 12 sentences were included as fillers which contained different syntactic structures (e.g., "the woman made the bunny…").

Procedure

The experiment was hosted on Gorilla Experiment Builder and consisted of 36 trials (24 test trials and 12 filler trials), split across two blocks. A new randomised order of trials was presented to each participant. A short rest period could be taken in between blocks.

Results

We first excluded responses that did not refer to either an instrument or modifier continuation (e.g., "The woman found the lion with the help of many tourists"). Of the remaining "relevant" continuations, responses were coded as 1 if it referred to an instrument continuation or 0 if it referred to a modifier continuation.

Appendix 1 presents verb-specific proportions of instrument continuations. For verbs that were classified as having a pre-existing instrument bias in Experiments 1–3, the mean proportion of instrument continuations was 0.84, compared to 0.34 for the modifier-biased verbs. To statistically compare the relative strength of bias across verb bias conditions, we created 'bias strength' scores for each verb. For the instrument-biased verbs, this was simply the proportion of instrument continuations, whereas for each modifier-biased verb, we subtracted the proportion of instrument continuations from 1. This meant that across verb bias conditions, larger values of bias strength reflected a relatively stronger bias towards the *assigned verb bias*. We then performed an independent-samples *t*-test to compare bias strength across verb bias conditions, which revealed a statistically significant difference [$t(22) = 2.71$, $p = .013$, $d = 1.11$], suggesting that verbs classified as having a pre-existing instrument bias are more strongly biased towards the instrument interpretation (*Mbias strength* = 0.84; *SD* = 0.13) than verbs classified as modifier-biased are biased towards the modifier interpretation ($M = 0.66$; $SD = 0.18$). Indeed, three verbs that were classified as modifier-biased (*located*, *pinched*, *squeezed*) elicited an instrument continuation more frequently than a modifier continuation (*M proportion of instrument continuations* = 0.55, 0.60, 0.55, respectively), suggesting these verbs may be more strongly biased towards the instrument interpretation.[6]

To further probe the effect of pre-existing bias strength on verb-bias priming, and as pre-registered, we included bias strength as a continuous predictor variable (z-scored) into a linear regression model analysing the priming data from Experiments 2 and 3. The dependent measure for this analysis was called 'priming magnitude'. To calculate priming magnitude for each instrument-biased verb, we subtracted the mean proportion of instrument interpretations in the primed from the unprimed condition, whereas the reverse subtraction was performed for the modifier-biased verbs (i.e,. primed – unprimed). This meant that positive priming magnitude scores corresponded to priming in the predicted direction for each verb bias condition (i.e., fewer instrument interpretations following priming to the modifier interpretation for instrument-biased verbs, vice versa for modifier-biased verbs). As 'experiment' (as well as verb bias condition) was included as a (categorical) predictor variable, priming magnitude was calculated separately for Experiments 2 and 3, meaning each verb contributed two priming magnitude scores to the model. Interestingly, bias strength significantly predicted priming magnitude ($B = 0.04$, $SE = 0.02$, $t = 2.04$, $p = .048$), with more strongly biased verbs associated with stronger verb-bias priming (see Fig. 6). There were no other significant main effects or interactions (all p's $> .411$).

Discussion

The aims of Experiment 4 were two-fold. First, it compared the relative strength of bias towards the instrument and modifier interpretation, on a verb-specific level, in the instrument and modifier-biased

[6] We repeated the analyses in Experiments 2 and 3 after removing these three "problematic" verbs from the data. These results were essentially identical, with no verb-specific priming in the modifier-biased condition in either experiment.

conditions, respectively. The results revealed statistically stronger biases in the instrument-biased condition, with some verbs classified as modifier biased appearing to have a stronger bias towards the instrument interpretation. Second, we explored the predictive function of bias strength on the verb-bias priming data collected in Experiments 2 and 3. This analysis revealed a significant relationship between bias strength and priming, with more strongly biased verbs associated with stronger verb-bias priming. Ultimately, given the contingency between bias strength and priming, and with stronger biases overall in the instrument-biased condition, we believe these two findings provide an explanation for why verb-bias priming was only evident with instrument-biased verbs in Experiments 2 and 3. We detail our reasons for this in the General Discussion.

General Discussion

Research into word-meaning priming has revealed an important contribution of learning and memory processes in guiding online lexical processing (Gaskell et al., 2019; Rodd et al., 2016), with the memory of recent linguistic episodes contributing to the comprehension of related linguistic material at a later point in time. However, whether these same processes impact syntactic processing is less clear, which was investigated in the present research. To do so, we adopted a verb-bias priming paradigm (Ryskin et al., 2017) to measure whether prior experiences of specific verbs in certain syntactic structures influences how the same verbs are processed in the future in syntactically ambiguous contexts. Initially, though, in Experiment 1, we confirmed prior findings (Ryskin et al., 2017; Snedeker & Trueswell, 2004) that verbs which may appear in a *with* prepositional phrase have a pre-existing bias for either an instrument or modifier interpretation, and that these biases are recruited online to resolve syntactic ambiguities. These results also confirmed the sensitivity of a forced-choice paradigm, similar to Branigan et al. (2005), in detecting this pre-existing verb bias effect.

In Experiment 2, for each participant, half of the verbs were initially primed towards their dispreferred interpretation in an exposure phase, and were re-encountered, along with unprimed verbs, ~20 min later in a test phase where both syntactic interpretations were viable (as in Experiment 1). A significant interaction between priming and pre-existing verb bias was found, indicating that primed verbs were more likely to elicit the dispreferred interpretation relative to unprimed verbs from the same verb bias condition. Hence, we found evidence of verb-bias priming (Ryskin et al., 2017), although when we unpacked the interaction, priming was only statistically significant for pre-existing instrument-biased verbs. In Experiment 3, a ~ 12-hour delay that included a period of sleep separated the exposure and test phases, allowing us to measure the maintenance of verb-bias priming over the longer term. However, our results were less clear. We did not find an interaction between priming and pre-existing verb bias, suggesting that the effect of priming is not observed over a 12-hour period. That said, there was again a significant simple effect of priming for the instrument-biased verbs. The results from an exploratory analysis in which the data was collapsed across Experiment 2 and Experiment 3 also revealed a significant verb-bias priming effect overall, and specifically in relation to the instrument-biased verbs. Finally, in Experiment 4, we found evidence to suggest that the strength of pre-existing bias towards the assigned pre-existing verb bias differed significantly between instrument and modifier-biased verbs, with stronger biases in the instrument-biased condition. The strength of bias also predicted the magnitude of verb-bias priming, akin to the modulating effect of pre-existing syntactic and semantic biases on syntactic and word-meaning priming, respectively.

Our primary goals were to address the issues of longevity and memory on verb-bias priming. If verb-bias priming is an indicator of how we update our long-term biases about likely syntactic structures in the face of syntactic ambiguity, then this kind of priming must be reasonably long-lived. Further, the basis of such an effect in memory would need to be determined. We provided a parallel with the literature on word-meaning priming, where memory for recent experiences of words interpreted in a particular way is certainly preserved over minutes and hours, and can be consolidated across sleep, consistent with a role for episodic memory in comprehension and updating of lexical knowledge (Gaskell et al., 2019). In terms of longevity then the key contribution of the current work is to show that verb-bias priming

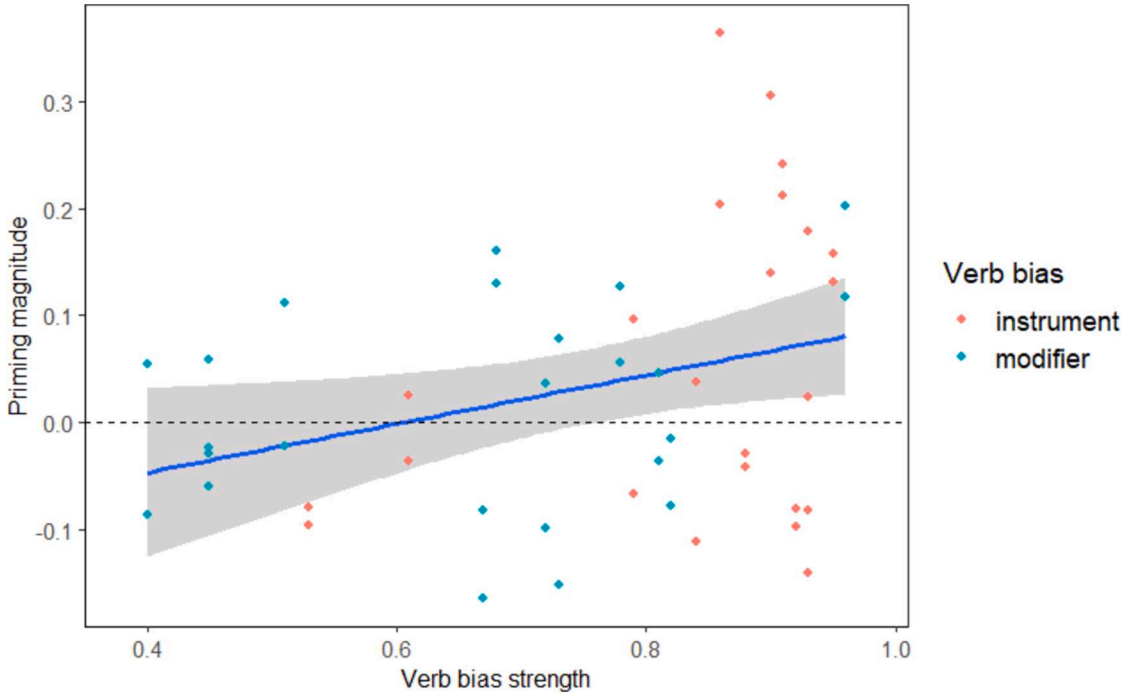

Fig. 6. The relationship between verb bias strength (Experiment 4) and priming magnitude in Experiments 2 and 3. The linear relationship was plotted using the geom_smooth (method = "lm") function in R. Individual points represent by-verb mean scores. The dashed horizontal line represents a numerical priming effect of zero.

certainly lasts for at least 20 min, and there is also some (weaker) evidence that it remains across 12 h including sleep. This places verb-bias priming in the domain of a memory effect, and cannot be explained in terms of residual activation in a processing network. As to exactly how this kind of priming is supported in memory systems is discussed in the next section.

The mechanisms of verb-bias priming

In the introduction, we outlined alternative mechanisms that could potentially underpin verb-bias priming. The first proposed mechanism concerned residual activation processes. Following Pickering and Branigan's (1998) model of the lexical boost in syntactic priming, sentence processing in the exposure phase could have triggered temporary residual activation between the verb representation and associated syntactic structure, facilitating the usage of the same verb-structure combination later. However, as mentioned, this is an unlikely explanation, at least concerning the timescales with which priming has so far been observed. Residual activation is assumed to dissipate quite quickly (e.g., within a few minutes), meaning it has a temporally limited influence on syntactic processing (Hartsuiker et al., 2008; Pickering & Branigan, 1998). Ryskin et al. (2017) observed within-session priming over a ~ 1-minute interval with a median of six interleaving filler trials between prime and test, which is conceivably within the time-domain of a residual activation account, particularly given that each verb was primed on multiple trials. However, it seems unlikely that residual activation in a processing network could remain across a period of 20 min, with substantial linguistic and other types of processing taking place in the intervening period. Similar to the word-meaning priming literature, we turn to learning and memory systems in order to understand how recent syntactic experiences of verbs can be preserved and influence later comprehension.

One possibility is that episodic memory supports verb-bias priming. According to the episodic context account (Gaskell et al., 2019), effects such as word-meaning priming are supported by contextual information being encoded within a context-specific representation in episodic memory, which can be used, alongside long-term linguistic knowledge, to support comprehension of the ongoing discourse involving previously encountered words. The theory thus predicts that the longer-term maintenance of priming is facilitated by sleep-related consolidation of episodic knowledge, a prediction that has been supported by empirical studies in the literature (Gaskell et al., 2019; Mak et al., 2023). In the current study, we found evidence for the longer-term priming of syntactic structure in relation to specific verbs: when a ~ 20-minute delay separated exposure to the dispreferred syntactic structures for specific verbs and the re-exposure of verbs in syntactically ambiguous contexts (Experiment 2), prior exposure increased the likelihood of instrument-biased verbs adopting the modifier interpretation. When the delay period was increased to ~ 12 h with a period of sleep (Experiment 3), the interaction between priming and pre-existing verb bias was non-significant. This suggests that the effect of exposure was more limited ~ 12 h later, possibly implicating a weak or absent sleep-consolidation effect. That said, there was a statistically significant simple effect of priming for the instrument-biased verbs (as with Experiment 2). Hence, while the current results provide preliminary evidence that verb-bias priming persists over a ~ 12-hour interval with sleep, they do not necessarily require the involvement of sleep-related consolidation of verb-specific, episodic memories encoded in the exposure phase. However, when taken together with complementary results from the word-meaning priming literature (Curtis et al., 2022; Gaskell et al., 2019; Mak et al., 2023), we suggest that the most parsimonious account of the current data is that, consistent with the episodic context account (Gaskell et al., 2019), syntactic information may be encoded within context-specific episodic representations, which not only contribute to lexical comprehension, but also to syntactic and verb-specific processing at a later time point. Future work is nonetheless required to provide more direct support for the episodic context account, particularly by comparing verb-bias priming between participants who slept and remained awake soon after exposure.[7] This could be facilitated by establishing a paradigm that is capable of eliciting stronger effects than those observed here. Nonetheless, our findings imply that some types of verb-bias priming are maintained when participants sleep soon after initial exposure.

In the introduction we mentioned the distinction between syntactic priming and verb-bias priming: the former is typically characterised as an abstract form of priming which does not depend on lexical repetition, whilst the latter is specifically concerned with priming verb-specific information. This raises the possibility that respective priming effects depend on separable mechanisms; indeed, syntactic priming is present in patients with episodic memory deficits (Ferreira et al., 2008; Heyselaar et al., 2017) which we have argued may underlie verb-bias priming. Episodic memory may, therefore, contribute differently to different aspects of syntactic processing, and may be particularly involved in monitoring the syntactic structures that specific verbs are encountered in based on statistical regularities in the linguistic environment (Ryskin et al., 2018). Speculatively, medial temporal lobe (MTL) structures that are implicated with episodic memory would be particularly well-suited for this function due to pattern separation mechanisms, which allow distinct, non-overlapping representations to be encoded (Rolls, 2013; Yassa & Stark, 2011). This could allow contextual information that is encoded for one verb to be distinct, and applied independently, from the information encoded for another verb.

That said, we acknowledge that with the current data, we cannot rule out the possibility that alternative mechanisms may also contribute to verb-bias priming. One possibility, and similar to the immediate alteration account of word-meaning priming (Gilbert et al., 2018; Rodd et al., 2016), is that existing verb-structure knowledge in the syntactic system is immediately adjusted based on linguistic input as a result of implicit learning (Chang et al., 2006; Ivanova et al., 2012; Peter et al., 2015; Twomey et al., 2014). According to Chang et al.'s (2006) Dual-Path model of syntactic priming, the syntactic system generates a set of lexical predictions during discourse processing. The difference, or error signal, between the predicted and the actual word is then used to make direct adjustments to abstract syntactic representations. However, because predictions are made on the basis of specific verbs, this allows the syntactic system to additionally acquire and update knowledge for specific verb-structure links. This was demonstrated in Peter et al. (2015), who used a simple dynamics model to simulate the formation of verb-specific structural biases based on language input (see also Twomey et al., 2014). Put simply, due to error-based learning, the bias for a certain verb-structure combination increases if that combination is regularly encountered. In adults, however, the learning rate from a single encounter is quite small (compared to children, reflecting a reduction in neural plasticity). Hence, a single verb-structure encounter is unlikely to instigate drastic changes in pre-existing bias, especially to the extent of altering how a verb is later interpreted in an ambiguous context. Speculatively, though, multiple verb-specific exposures – such as four exposures to the dispreferred interpretation, as in our exposure phase – could be sufficient to instigate enough change in bias to the dispreferred interpretation to positively enhance its preferability, relative to the same verb in the unprimed condition. Indeed, because learning takes place immediately in relevant syntactic systems, these models would predict similar patterns of priming across time, which could be supported by the continued simple priming effect for the instrument-biased verbs.

[7] To reiterate, we maintained flexibility in our testing plan to explore a potential wake condition to compare against the results of Experiment 3. However, due to the modest effects in Experiment 3, we deemed it unworthy to proceed with a wake condition with this particular paradigm.

The role of bias strength on Verb-Bias priming

The sentence completion data from Experiment 4 suggest that verbs classified as instrument-biased are more strongly biased towards the instrument interpretation relative to the strength of bias that verbs classified as modifier-biased have for the modifier interpretation. In addition, the strength of verb-specific biases was found to predict the magnitude of verb-bias priming in Experiments 2 and 3. This finding has strong parallels to the *inverse preference* or *prime surprisal effect* in syntactic priming (Bernolet & Hartsuiker, 2010; Fine & Jaeger, 2013; Jaeger & Snider, 2013; Peter et al., 2015) and the modulating effect of meaning bias on word-meaning priming (Curtis et al., 2022; Rodd et al., 2013).

Collectively, the results from Experiment 4 are important because, we believe, they provide a reasonable explanation as to why we only detected significant verb-bias priming with the instrument-biased verbs. This is because the memory and learning frameworks discussed in the previous section (episodic memory and implicit learning) would independently predict stronger verb-bias priming for verbs with stronger pre-existing biases. In terms of episodic memory, van Kesteren et al. (2012) propose that the MTL is preferentially recruited for memory processing when an external event is perceived as incongruent given pre-existing knowledge. In the context of our experiments, processing an instrument-biased verb with the modifier interpretation is presumably more incongruent than processing a modifier-biased verb with the instrument interpretation due to the relatively strong pre-existing bias in the instrument-biased condition. Theoretically, this would lead to a stronger episodic memory trace of the (more incongruous) event that may provide a greater source of support to verb-specific processing in the future. In terms of implicit learning, recall that (syntactic) priming may be explained by the updating of verb-structure links through error signals based on lexical predictions (Chang et al., 2006; Peter et al., 2015; Twomey et al., 2014). Crucially, because these predictions are partially sourced from knowledge of preceding verbs in discourse, verbs with a relatively strong bias towards a particular structure will sway the syntactic system to generate a lexical prediction that is consistent with that structure. Hence, more strongly-biased verbs may generate more specific predictions, resulting in a larger error signal, and hence greater learning and priming, when this prediction is not met. Indeed, such mechanisms can successfully model the inverse preference effect in syntactic priming (Peter et al., 2015).

Thus, the imbalance in verb-specific biases likely contributed to the imbalance in verb-bias priming between instrument and modifier-biased verbs. Although interesting, this was not intentional, and future work should consider using verbs that are more strongly biased towards the modifier interpretation to encourage verb-bias priming in this condition. That said, the mean proportion of instrument continuations in Experiment 4 overall was 0.58, suggesting a slight, general preference for the instrument interpretation, at least concerning the 24 verbs used in this study. As we discussed earlier, it is also important to consider the role of the accompanying noun/object in a sentence context and how this might also contribute to resolving syntactic ambiguities. Recall that we diverged from the design of Ryskin et al. (2017) slightly by pairing verbs with semantically plausible objects (e.g., the verb *looked (at)* was paired with *telescope*), which likely contributed to the relative preference for the instrument interpretation in the modifier-biased condition. Yet, during typical discourse, the semantic relationship between verbs and nouns is an important facilitator to discourse processing (Do et al., 2011; Riaz & Girju, 2014). This raises the possibility that when dealing with syntactic ambiguities in semantically congruent contexts, the instrument interpretation may boast a slight bias in general, rendering fewer verbs with a particularly strong bias for the modifier interpretation. The role of verb-noun pairings on syntactic ambiguity resolution presents an interesting avenue for future work to explore.

Conclusion

This study investigated the mechanisms of verb-bias priming to gain insight into the possible role of learning and memory processes in supporting online syntactic processes. To achieve this, individual verbs were encountered in their dispreferred syntactic structures and we subsequently measured the effect of this prior exposure at different time points in syntactically ambiguous contexts. In Experiment 2, we found evidence that exposure to the dispreferred interpretation influenced how the same verbs were processed ~ 20 min later, extending previous findings which observed verb-bias priming at shorter intervals of ~ 1 min. In Experiment 3, we found modest evidence to suggest that the effect of exposure may persist ~ 12 h later with a period of overnight sleep. The relative longevity of the observed effects rules out a residual activation processing account, which would predict more short-lived priming effects. Instead, our findings suggest that verb-bias priming is a consequence of memory systems being applied to the linguistic input. We argue that these effects are most easily explained by the episodic context account, which can also accommodate a growing set of results from analogous word-meaning priming experiments. However, the data are also consistent with implicit learning accounts of verb-structure knowledge acquisition, which similarly predict prolonged effects as a result of the immediate updating of syntactic knowledge within the syntactic system. Interestingly, both episodic memory and implicit learning frameworks predict priming to be modulated by pre-existing bias strength, which could explain why we only observed significant priming with the (more strongly biased) instrument-biased verbs. More broadly, these results emphasize the importance of learning and memory systems in allowing comprehenders to utilise their recent (20 min), and perhaps more distant (12 h), experiences with individual verbs to improve the ease with which syntactic ambiguities, which are ubiquitous in natural language, can be resolved.

CRediT authorship contribution statement

Lewis V. Ball: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matthew H. C. Mak:** Writing – review & editing, Resources, Methodology, Conceptualization. **Rachel Ryskin:** Writing – review & editing, Methodology, Conceptualization. **Adam J. Curtis:** Writing – review & editing, Methodology, Conceptualization. **Jennifer M. Rodd:** Writing – review & editing, Funding acquisition, Conceptualization. **M.Gareth Gaskell:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. . The 24 verbs used in the experiments and their respective verb bias conditions

Verb	Verb bias condition	Proportion of trials that elicited the instrument interpretation in Ryskin et al. (2017; Experiment 1)	Proportion of relevant continuations in Experiment 4	Proportion of instrument continuations in Experiment 4
Bopped	Instrument	0.77	0.74	0.84
Cleaned	Instrument	0.60	0.99	0.95
Fed	Instrument	0.79	0.28	0.61
Hit	Instrument	0.69	0.87	0.91
Knocked (on)	Instrument	0.58	0.76	0.79
Petted	Instrument	0.69	0.70	0.53
Poked	Instrument	0.77	0.84	0.93
Scuffed	Instrument	0.77	0.90	0.86
Smacked	Instrument	0.79	0.89	0.92
Struck	Instrument	0.79	0.93	0.90
Teased	Instrument	0.79	0.93	0.88
Whacked	Instrument	0.79	0.92	0.93
Chose	Modifier	0.13	0.96	0.04
Felt	Modifier	0.46	0.78	0.32
Found	Modifier	0.04	0.79	0.28
Hugged	Modifier	0.46	0.72	0.22
Located	Modifier	0.04	0.91	0.55
Looked (at)	Modifier	0.10	0.83	0.27
Picked (out)	Modifier	0.10	0.89	0.19
Pinched	Modifier	0.33	0.73	0.60
Pointed (to)	Modifier	0.15	0.90	0.33
Selected	Modifier	0.04	0.91	0.18
Spotted	Modifier	0.13	0.86	0.49
Squeezed	Modifier	0.31	0.74	0.55

Data availability

The research data and code is available on the Open Science Framework (https://osf.io/wj3da/).

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