

Knowledge and learning of verb biases in amnesia

Rachel Ryskin^{a,b,*}, Zhenghan Qi^c, Natalie V. Covington^d, Melissa Duff^{cd}, Sarah Brown-Schmidt^e

^a Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, United States

^b Department of Speech, Language, and Hearing Sciences, Boston University, United States

^c Department of Linguistics and Cognitive Science, University of Delaware, United States

^d Department of Hearing and Speech Sciences, Vanderbilt University Medical Center, United States

^e Department of Psychology and Human Development, Vanderbilt University, United States

ARTICLE INFO

Keywords:

Hippocampal amnesia
Language processing
Eye-tracking
Syntactic ambiguity

ABSTRACT

Verb bias—the co-occurrence frequencies between a verb and the syntactic structures it may appear with—is a critical and reliable linguistic cue for online sentence processing. In particular, listeners use this information to disambiguate sentences with multiple potential syntactic parses (e.g., *Feel the frog with the feather.*). Further, listeners dynamically update their representations of specific verbs in the face of new evidence about verb-structure co-occurrence. Yet, little is known about the biological memory systems that support the use and dynamic updating of verb bias. We propose that hippocampal-dependent declarative (relational) memory represents a likely candidate system because it has been implicated in the flexible binding of relational co-occurrences and in statistical learning. We explore this question by testing patients with severe and selective deficits in declarative memory (anterograde amnesia), and demographically matched healthy participants, in their on-line interpretation of ambiguous sentences and the ability to update their verb bias with experience. We find that (1) patients and their healthy counterparts use existing verb bias to successfully interpret on-line ambiguity, however (2) unlike healthy young adults, neither group updated these biases in response to recent exposure. These findings demonstrate that using existing representations of verb bias does not necessitate involvement of the declarative memory system, but leave open the question of whether the ability to update representations of verb-specific biases requires hippocampal engagement.

1. Introduction

Listeners represent the co-occurrence frequencies between verbs and the syntactic structures they appear with—verb biases—and deploy this knowledge during online sentence processing. Words within sentences combine in different ways such that the prepositional phrase “with the feather” in a sentence like “*Feel the frog with the feather*” can attach to the noun, indicating *which frog*, or it can attach to the verb, indicating *how to feel it*. Knowledge about the statistical regularities with which particular verbs are used in one syntactic construction or another guides interpretation of these ambiguities (Garnsey, Pearlmutter, Myers, Lotocky, 1997; Snedeker & Trueswell, 2004). Moreover, this lexically-specific knowledge is updated based on recent linguistic experience (Coyle & Kaschak, 2008; Ryskin, Qi, Duff, & Brown-Schmidt, 2017a, 2017b, 2018).

In the present research, we probe the neural mechanisms that support the use of these statistical regularities in online syntactic processing. Our approach combines the study of neuropsychological patients with severe relational memory impairment, with psycholinguistic

techniques to probe the online processing of sentences in rich contexts. In particular, we investigate a role for the hippocampal relational memory system, in light of its processing capabilities, in the online processing and updating of verb bias information. While previous work has demonstrated that offline identification of syntactic ambiguity is intact in patients with medial temporal lobe damage (e.g. Schmolck, Stefanacci, & Squire, 2000), emerging research examining language in rich contexts and with online measures points to a critical role for hippocampal relational memory in language processing (Duff & Brown-Schmidt, 2012, 2017).

1.1. Verb bias use in language processing

Language-wide distributional characteristics of specific verbs guide the online and offline resolution of prepositional phrase (PP) attachment ambiguities in sentences with globally ambiguous syntactic structures such as *Feel the frog with the feather* (Snedeker & Trueswell, 2004). In a norming study, Snedeker and Trueswell (2004) characterized a set of verbs based on the relative degree to which a sentence

* Corresponding author at: Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, United States.
E-mail address: ryskin@mit.edu (R. Ryskin).

containing a specific verb and a *with* prepositional phrase is completed by a modifier noun (e.g. choose the dog with the pointy ears) or an instrument (e.g. tickle the teddy bear with the feather)—a difference in syntactic structure that also changes the meaning of the sentence. Verbs were then categorized as modifier-biased (i.e., PPs tended to attach to the head noun), instrument-biased (i.e., PPs tended to attach to the verb), or equi-biased (verbs that were in-between). In a subsequent study using the visual-world eye-tracking technique (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) to examine online processing, other participants listened to spoken instructions in which the verbs appeared in globally ambiguous syntactic constructions while viewing a scene with toys that afforded both an instrument and a modifier based interpretation. Snedeker and Trueswell (2004) found that listeners resolved these global ambiguities by relying on information about the verb's lexical bias—the likelihood of the co-occurrence of the verb and each syntactic alternative that can be associated with it (see also Boland, 1997; Boland, Tanenhaus, Garnsey, & Carlson, 1995; Garnsey et al., 1997; MacDonald, Pearlmutter, & Seidenberg, 1994; Spivey & Tanenhaus, 1998; Spivey-Knowlton & Sedivy, 1995; Spivey-Knowlton, Trueswell & Tanenhaus, 1993; Taraban & McClelland, 1988; Trueswell, 1996; Trueswell, Tanenhaus, & Kello, 1993; Wilson & Garnsey, 2009).

These findings point to a critical role for knowledge of the mapping between verbs and structures in on-line language processing. Here, we explore whether a brain structure better known for its role in memory – the hippocampus – may play a central role in online processing of verb bias information. The hippocampus has long been known to play an important role in relational memory. It has been implicated in encoding the enduring representations of the co-occurrences of people, places, and things as well as their spatial and temporal relations (Cohen & Eichenbaum, 1993; Davachi, 2006; Eichenbaum & Cohen, 2001; Ryan, Althoff, Whitlow, & Cohen, 2000). The hippocampus has also been tied to the fast, *on-line* binding of relational information between co-occurring stimuli (Barense, Gaffan, & Graham, 2007; Hannula, Tranel & Cohen, 2006; Ranganath and D'Esposito, 2001), and to memory-perception comparisons (e.g., Duncan, Curtis, & Davachi, 2009; Harrison, Duggins, & Friston, 2006; Kim, Lewis-Peacock, Norman, Turk-Browne, 2014; Kumaran & Maguire, 2007; Long, Lee, & Kuhl, 2016). Further, recent work has suggested an important role for the hippocampus in aspects of language processing with similar processing demands to online syntactic disambiguation (Kurczek, Brown-Schmidt, & Duff, 2013; Piai et al., 2016; Blank et al., in preparation; Rubin, Brown-Schmidt, Duff, Tranel, & Cohen, 2011). For instance, patients with hippocampal amnesia struggle to resolve ambiguity during online sentence comprehension when interpretation hinges on binding an ambiguous pronoun to the appropriate antecedent (e.g., *Melissa* is playing violin for Debbie as the sun is shining overhead. *She* is wearing a blue dress). The online processing of verb bias information may similarly engage hippocampal relational binding mechanisms as it requires in-the-moment retrieval of verb-specific information and binding of the prepositional phrase to what it modifies.

Alternatively, other evidence suggests that many aspects of syntactic processing do not rely on the hippocampal declarative memory system. For example, artificial grammar learning abilities and susceptibility to syntactic priming remain intact in patients with amnesia (Ferreira, Bock, Wilson, & Cohen, 2008; Knowlton, Ramus, & Squire, 1992; Schmolck et al., 2000; cf. Chang, Janciauskas, & Fitz, 2012; MacKay, Stewart, & Burke, 1998). These findings are often taken as evidence that artificial grammar learning and syntactic priming tap procedural memory mechanisms. Thus, whether processing of verb bias takes place within, or in concert with, the hippocampal declarative memory system is an open question.

Further, verb bias information is not static, but rather is malleable based upon experience. Previous research has shown that experience with a particular syntactic structure facilitates processing of and even expectation for that structure in the future (Fine & Jaeger, 2013; Fine,

Jaeger, Farmer, & Qian, 2013; Kaschak & Glenberg, 2004; Luka & Barsalou, 2005; Tooley, Swaab, Boudewyn, Zirnstein, & Traxler, 2014; Tooley, Traxler, & Swaab, 2009; Wells, Christiansen, Race, & MacDonald, 2009). Moreover, listeners' preferences for lexeme-specific syntactic attachment can be shaped by recent experience (Chang, Dell, & Bock, 2006; Chang, et al., 2012; Jaeger & Snider, 2013). Ryskin et al. (2017a, b, 2018) demonstrated that representations of the biases of specific verbs are malleable and can be updated through exposure to new structure-verb co-occurrence statistics. The use and updating of verb-structure relations based on recent linguistic experience requires the tracking and rapid updating of arbitrary co-occurrence information, thus we postulate that these mechanisms may place key demands on the hippocampal memory system.

A role for the hippocampus in tracking and updating verb bias information based on experience would be consistent with recent evidence of hippocampal involvement in statistical learning (see Schapiro, Turk-Browne, Botvinick & Norman, 2017). Neuroimaging data point to a role for hippocampus in the representation of statistical regularities in healthy adults (e.g. Turk-Browne, Scholl, Chun, & Johnson, 2009; Schapiro, Kustner, & Turk-Browne, 2012). Further, data from one patient with complete bilateral hippocampal loss indicate a failure to learn patterns of temporal co-occurrence in a variety of stimuli (Schapiro, Gregory, Landau, McCloskey, & Turk-Browne, 2014; cf. Covington, Brown-Schmidt, & Duff, 2018). On the other hand, patients with hippocampal damage have been shown to demonstrate learning of patterns in linguistic material, such as artificial grammar learning (Knowlton et al., 1992), syntactic priming (Ferreira et al., 2008), and new dialectal variants tied to a particular speaker (Trude, Duff, & Brown-Schmidt, 2014). Thus, whether the hippocampus is critical in supporting the tracking of co-occurrences of verbs with syntactic structures and learning of new verb-biases is an open question.

In the present work, we take a hybrid neuropsychological – psycholinguistics approach to examining the biological memory systems that support the real-time processing of lexical biases in syntactic ambiguity resolution. In Experiments 1 and 2, we used paradigms modeled on Snedeker & Trueswell (2004), with real-world objects and a computerized paradigm respectively, to examine the use of verb bias in patients with hippocampal lesions as well as healthy, demographically-matched comparison participants. To preview, patients with amnesia, as well as older adult comparisons made use of verb bias information in order to resolve global syntactic ambiguity in the moment. In Experiment 3, we aimed to test whether patients with amnesia can not only use verb bias information online but also update those biases based on recent exposure. We employed a paradigm we have successfully used in the past to demonstrate dynamic updating and use of verb biases in healthy young adults (Ryskin et al., 2017a, 2017b, 2018). Amnesic and comparison participants were exposed to sets of—initially equi-biased—verbs that were exclusively tied to one of two possible syntactic structures (either instrument or modifier-interpreted *with* phrases) by a disambiguating context. We then measured offline behavioral responses and eye-fixations on globally ambiguous test trials to evaluate whether the listeners' interpretation of a specific verb-argument structure was influenced by the syntactic structures that the verb had been paired with previously.

2. General methods

Across the three experiments, participants included 5 individuals with bilateral hippocampal damage (one female) and severe declarative memory impairment and 8 healthy comparison participants. Etiologies of the patients with hippocampal amnesia included anoxia/hypoxia (1846, 2363, 2563) resulting in bilateral hippocampal damage, and herpes simplex encephalitis (HSE) (1951, 2308), resulting in more extensive bilateral medial temporal lobe damage affecting the hippocampus, amygdala, and surrounding cortices. Structural MRI data were available for 4 of the 5 patients (excluding 2563) (Fig. 1) and

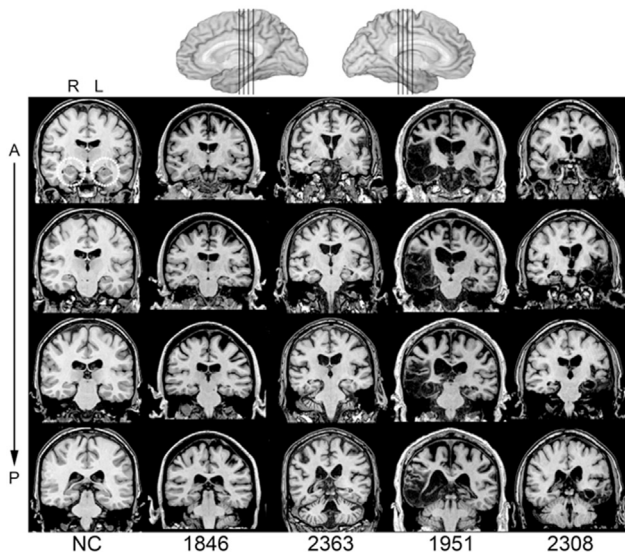


Fig. 1. Magnetic resonance scans of hippocampal patients. Images are coronal slices through four points along the hippocampus from T1-weighted scans. R = right; L = left; A = anterior; P = posterior; NC = a healthy comparison brain.

volumetric analyses performed on 3 of the 5 patients revealed significant reduction to the hippocampus bilaterally with volumes reduced by at least 2.64 studentized residuals compared to age matched healthy comparison participants (Allen, Tranel, Bruss, & Damasio, 2006). Visual inspection of a CT scan from patient 2563, who wears a pacemaker, confirmed damage limited to hippocampus.

Performance on tests of neuropsychological functioning revealed a severe and selective impairment in episodic/declarative memory functioning while performance across other cognitive domains was within normal limits (Table 1). The Wechsler Memory Scale–III General Memory Index scores for each participant were at least 25 points lower than their scores on the Wechsler Adult Intelligence Scale–III, and the mean difference between Full Scale IQ and General Memory Index was 38.5 points. The average Delayed Memory Index was 61.4, which is 3 standard deviations below population means. This deficit in episodic/declarative memory was observed in the context of otherwise intact cognitive abilities. Participants performed within normal limits on standardized neuropsychological tests of intelligence, language, and

Table 1
Demographic and neuropsychological characteristics of patients with amnesia.

Subject	Expt.	Sex	Birth Year	Hand.	Ed.	Etiology	HC Damage	HC Volume	WAIS III FSIQ	WMS III GMI	BNT	TT	WCS (Cat)
1846	1, 2, 3	F	1963	R	14	Anoxia	Bilateral HC	−4.23	84	57	43	41	6
2363	1, 2	M	1956	R	18	Anoxia	Bilateral HC	−2.64	98	73	58	44	6
2563	1, 3	M	1955	L	16	Anoxia	Bilateral HC	N/A	102	75	52	44	6
1951	2, 3	M	1952	R	16	HSE	Bilateral	−8.10	106	57	49	44	6
2308	1	M	1956	L	16	HSE	HC + MTL Bilateral HC + MTL	N/A	87	45	52	44	N/A
Group Summary		1F 4M		3R 2L	16 (± 1.4)			−5.0 (± 2.8)	95.4 (± 9.5)	59.0 (± 12.2)	51.8 (± 5.5)	43.4 (± 1.3)	6

Expt. = which of the three Experiments this person participated in. HC = hippocampus (participants with bilateral hippocampal damage). Hand. = Handedness. Ed. = years of completed education. HSE = Herpes Simplex Encephalitis. + MTL = damage extending into the greater medial temporal lobes. N/A = no available data. Volumetric data are z-scores as measured through high resolution volumetric MRI and compared to a matched healthy comparison group (see Allen et al., 2006, Buchanan, Tranel, & Adolphs, 2005 for additional details). WAIS-III FSIQ = Wechsler Adult Intelligence Scale–III Full Scale Intelligence Quotient. WMS-III GMI = Wechsler Memory Scale–III General Memory Index. BNT = Boston Naming Test. TT = Token Test. WCS = Wisconsin Card Sorting Task; Cat = Number of categories achieved out of six. **Bolded** scores are impaired as defined as 2 or more standard deviations below normative data.

executive function.

Comparison participants were eight healthy individuals matched pairwise on age, handedness, sex, and education. All participants were native, monolingual speakers of North American English with normal or corrected-to-normal hearing and vision. Due to scheduling conflicts, not all patients with hippocampal amnesia participated in all studies. One healthy comparison participant completed all three of the experiments, three healthy comparisons participated in two of the three experiments, and one comparison only participated in the first experiment.

3. Experiment 1

The goal of Experiment 1 is to test the use of verb bias in patients with hippocampal amnesia using an experimental paradigm modeled on Snedeker and Trueswell (2004).

3.1. Participants

Patients 1846, 2308, 2363, and 2563 participated in Experiment 1 and were 55.5 years old and had 16.0 years of education, on average, at the time of data collection. The four demographically matched healthy comparison participants were 55.6 years old and had 17.3 years of education, on average.

3.2. Design & procedure

Participants sat in front of an inclined podium with a shelf in each quadrant on which toys could be placed, and a central opening for a camera that recorded the participants' eye-movements at 30 Hz. Another camera positioned behind the participant recorded their actions. The recorded instructions were played from a laptop computer through external speakers positioned at the top of the podium display. Participants were told that they would play a game involving following instructions. At the start of each trial, the experimenter placed the toys in each quadrant of the podium, introducing each by name as he did so. The mini-instruments attached to each animal were introduced as separate objects (e.g., "Here's a crayon, a pig, a flower, another flower, an elephant, and another crayon"). After naming the objects in this manner a second time, the experimenter played the pre-recorded instructions for the trial. Each trial began with an instruction to "look at the camera", followed by two other instructions. In critical trials the first instruction was the critical sentence and the second was a filler sentence. This procedure is modeled closely on the one described by Snedeker and Trueswell (2004). Each participant heard all 24 critical

sentences ordered pseudo-randomly so that no consecutive critical trials contained verbs with the same bias condition. Filler trials were randomly interspersed with the critical trials to mask the purpose of the experiment.

Each participant completed the same list of trials three times with different orders. As a result, each participant completed 72 critical trials. Testing was conducted over a series of 3 sessions, with all sessions for a given participant conducted within the span of a single week.

3.3. Materials

Both critical and filler trials included two instructions. In the critical trial, the first command is the critical sentence. 24 critical sentences and 72 filler sentences, all from the materials of [Snedeker and Trueswell \(2004\)](#), were recorded by a native English female speaker. Each critical sentence contained a target verb with either instrument bias, equi bias or modifier bias, followed by an animal name in direct object position, and an ambiguous *with* phrase, as in examples (1–3). The average critical sentence duration was 2.15 s and there was no significant difference among three bias conditions in duration ($F(2,21)=2.56$, $p = 0.101$). The filler sentences are unambiguous instructions using different verbs.

- (1) Tickle the frog with the feather. (Instrument bias)
- (2) Point at the pig with the flower. (Equi bias)
- (3) Choose the cow with the stick. (Modifier bias)

As shown in [Fig. 2](#), each critical sentence was accompanied by a set of toys: a target Animal with a small replica of the target instrument (e.g., a pig holding a flower), a distracter Animal with a small replica of the distracter instrument (e.g., an elephant holding a crayon), a target Instrument (e.g., a large flower) and a distracter Instrument (e.g., a large crayon). These toys made available both modifier and instrument interpretations of the *with* phrase. That is, the display contained a large flower with which to point at the pig, and a pig that had a flower. Due to our primary interest in the verb-bias manipulation, all critical sentences were presented in contexts comparable to the one-referent condition of [Snedeker and Trueswell's \(2004\)](#) experiment (we did not test the two-referent condition).

3.4. Coding

Trained coders, blind to the hypotheses of the study, categorized participants' actions as instrument actions (the participant performed the action on the target animal using the target instrument), modifier actions (the participant performed the action on the target animal using her hand), or mini-instrument actions (the participant used the mini-



Fig. 2. Experiment 1 toy layout for the sentence *Point at the pig with the flower*. The target animal is the pig, which is holding a flower. The target instrument is the big flower.

instrument attached to the target animal to carry out the action). Because the mini-instrument actions are potentially consistent with both an NP-attachment and a VP-attachment interpretation, six trials (5 in the patient group and 1 in the control group) coded as mini-instrument actions were removed from the eye-movement analysis as in [Snedeker & Trueswell \(2004\)](#). Four additional trials in the patient group were excluded from analysis because the participant did not act (2) or because the participant asked where the target animal was (1) or because the participant was out of the camera view (1).

Coders first marked the onset of each critical sentence and then participants' eye movements were coded frame by frame from video, played back without sound. Coders recorded where the participant was looking from the onset of the critical sentence until 3.2 s later. We coded looks to the four quadrants of the podium, away, and to the central camera. Frames were coded as missing if the participants' eyes were hidden. Four trials were removed from analysis, because participants made fixations to a quadrant of the podium in fewer than 1/3 of frames between the onset of the sentence and the average onset of the action (70 frames). As a result, of 576 possible trials, we eliminated a total of 39 trials (6.8%) from the eye-movement analyses.

3.5. Results

3.5.1. Actions

The participants' responses to the instructions were coded as instrument or modifier actions as described above. Participants in both groups were more likely to perform an instrument action in the instrument-biased condition than the equi-biased or modifier-biased conditions ([Fig. 3](#)).

All analyses were performed using the *lme4* package in R ([Bates, Maechler, Bolker, & Walker, 2015](#)). The action data were analyzed using mixed-effects logistic regression. The dependent measure was whether the participant made an instrument response or a modifier response. The model included random intercepts for participants and items, as well as random by-participant slopes for verb bias condition and random by-item slopes for participant group. Verb bias condition was entered as a pair of orthogonal contrast codes. The first contrast compared the instrument-biased condition (-0.66) to the average of the equi-biased (0.33) and modifier-biased (0.33) conditions. The second contrast compared the equi-biased (-0.50) condition to the modifier-biased (0.50) condition. Participant group was deviation coded (comparisons: -0.5 , amnesics: 0.5). The full set of parameter estimates is reported in appendix [Table A1](#). Instrument responses were significantly less likely ($b = -3.34$, $SE = 0.76$, $z = -4.42$, $p < 0.001$) in the equi-biased and modifier-biased conditions compared to the instrument-biased condition. There was no significant difference in participant actions between the modifier-biased condition and the equi-biased condition ($b = 0.74$, $SE = 0.97$, $z = 0.77$, $p = 0.44$). There was no main effect of participant group ($b = -0.63$, $SE = 1.34$, $z = -0.47$, $p = 0.64$) and verb bias condition did not interact with participant group (Contrast 1: $b = 1.15$, $SE = 1.05$, $z = 1.10$, $p = 0.27$; Contrast 2: $b = 0.79$, $SE = 1.23$, $z = 0.64$, $p = 0.52$).

3.5.2. Eye fixations

The plot of fixations over time ([Fig. 4](#)) suggests a similar pattern of results to [Snedeker and Trueswell \(2004\)](#) in the amnesic group. The amnesic participants seem to make more fixations to the target animal when the verb is modifier-biased than when it is equi-biased, and the instrument-biased verbs elicit the fewest fixations to the target animal. The reverse pattern is observed for fixations to the target instrument. This pattern is numerically weaker in the comparison participants.

We analyzed the data in three time windows in order to capture eye-movements elicited during both early and later portions of the sentence. All time windows were offset by 200 ms to account for the time needed to program and launch an eye movement ([Hallett, 1986](#)). The first time window started at the onset of the verb (e.g., *Point at the pig with the*

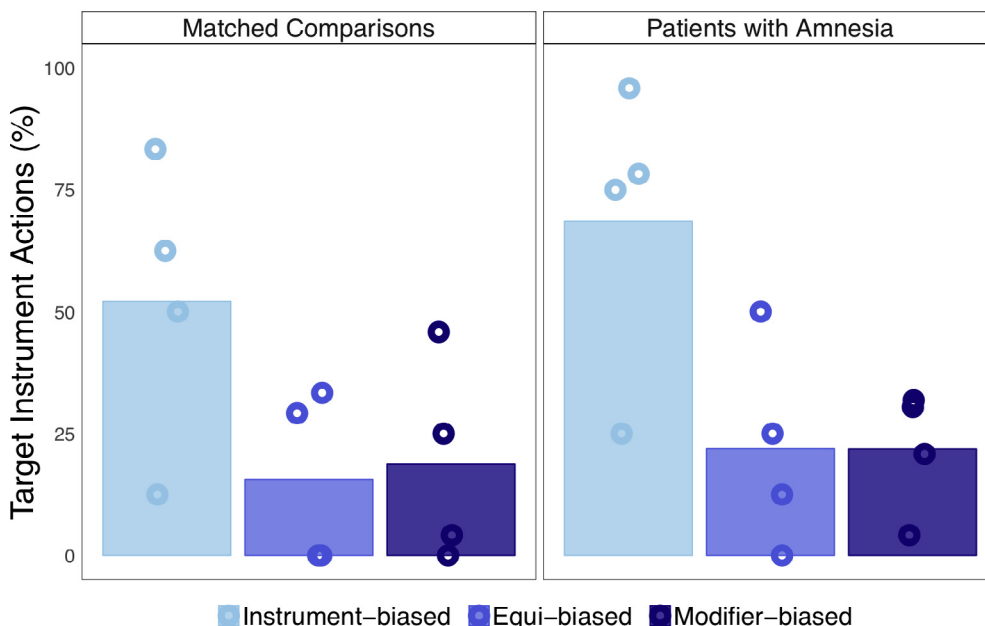


Fig. 3. Experiment 1: Proportion of instrument actions in three conditions (modifier-biased, equi-biased, and instrument-biased verbs) for persons with amnesia and matched comparison participants. Circles indicate performance of individual participants.

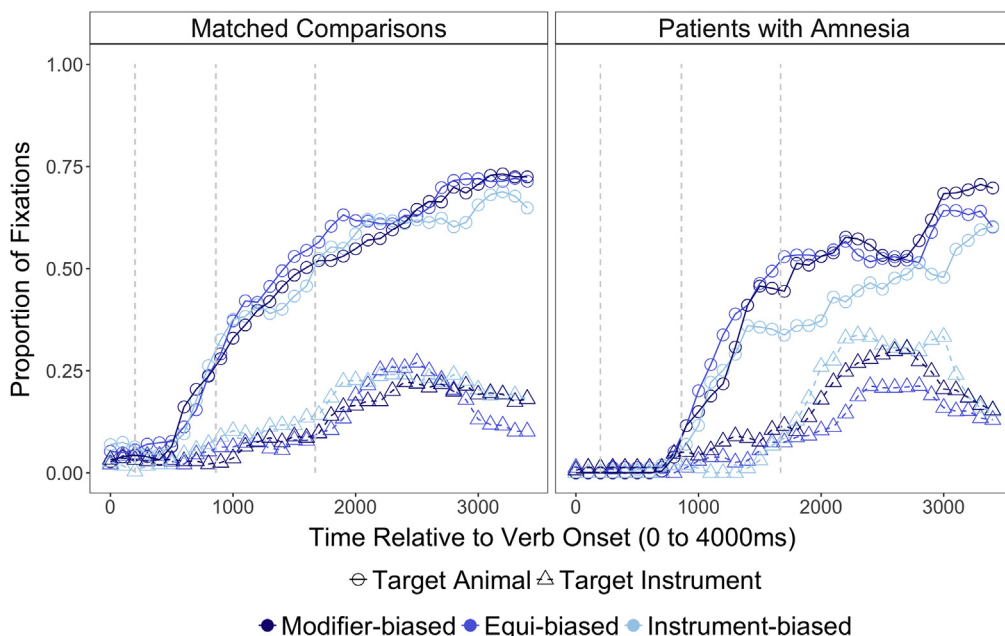


Fig. 4. Experiment 1: Proportion of gaze fixations in three conditions (modifier-biased, equi-biased, and instrument-biased) over time for persons with amnesia and demographically-matched comparison participants (graphs for each individual available in Supplemental Material S2). (Dashed lines indicate average beginnings of the three time windows used for analysis.)

flower) and ended at the onset of the first noun (e.g., pig). The average duration of the first time window was 659 ms. The second time window began at the onset of the first noun and ended at the onset of the second noun (e.g., flower). The average duration of the second time window was 808 ms. The third time window started at the onset of the second noun and ended 1500 ms later (the maximum duration of the second noun was 852 ms).

We fit mixed-effects linear regression models predicting eye fixations from participant group and verb bias condition, across the three time windows of interest. The dependent variable for these analyses was a measure of *Target Animal Advantage*: proportion of fixations to the target animal minus the proportion of fixations to the target instrument, with an empirical logit transformation applied to the proportions because the data were not normally distributed (see Barr, 2008 for a related approach). The model included random intercepts for participants

and items, as well as random by-participant slopes for verb bias condition, time window, and their interaction and random by-item slopes for participant group, time window, and their interaction (this was the maximal random effect structure justified by the design). Verb bias condition was entered as a pair of weighted¹ orthogonal contrast codes. The first contrast compared the instrument-biased condition (−0.66) to the average of the equi-biased (0.34) and modifier-biased (0.34) conditions. The second contrast compared the equi-biased (−0.50) condition to the modifier-biased (0.49) condition. Participant group was deviation coded (comparisons: −0.5, amnesics: 0.5). Time window was

¹ Coding is weighted by number of trials in each condition. Due to some missing trials (e.g., if a participant doesn't look at the screen within the time window) the contrasts are not exactly −2/3, 1/3, 1/3 or −1/2, 1/2 (see Appendix A for number of observations).



Fig. 5. Experiment 2: Example screen during a critical trial corresponding to the sentence “Pet the duck with the hat”. The duck wearing the hat is the target animal. The hat is the target instrument. The bird with the sponge is the competitor animal. The sponge is the competitor instrument.

Helmert coded (Contrast 1: time window 1 = -0.66 ; time window 2 = 0.33 , time window 3 = 0.33 ; Contrast 2: time window 1 = 0 ; time window 2 = -0.5 , time window 3 = 0.5). All analyses were performed using the lme4 package in R (Bates et al., 2015) with p-values estimated using Satterthwaite’s approximation performed by the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2015). The full set of estimated parameters from this model is summarized in appendix Table A2. There was a significant effect of time window, such that Target Animal Advantage was larger in the second and third time windows relative to the first ($b = 2.00$, $SE = 0.58$, $t = 3.44$, $p = 0.003$). There were no main effects of participant group ($b = 0.79$, $SE = 0.62$, $t = 1.28$, $p = 0.25$) or verb bias condition (Contrast 1: $b = 0.53$, $SE = 0.78$, $t = 0.67$, $p = 0.51$; Contrast 2: $b = -0.03$, $SE = 0.91$, $t = -0.03$, $p = 0.97$), nor did these significantly interact with time window.

3.6. Discussion

The data from this experiment provide some evidence that patients with amnesia use verb bias information while processing global syntactic ambiguities as measured by their offline, behavioral responses. The statistical analysis of the eye-movements does not reveal significant differences across conditions. Yet, the apparent lack of such an effect in the comparison group alongside a trend towards a verb bias effect for the patients, points to potentially noisy data and a low-power design. Similarly, the action data do reveal a significant difference between the Instrument-biased condition and the Equi-biased and Modifier-biased conditions, consistent with Snedeker and Trueswell (2004), but no difference between the Equi-biased and Modifier-biased conditions. Thus, these data suggest that the current design may not have had enough power to robustly detect the effects of verb bias. These observations suggest that a replication with a larger number of trials is necessary to draw strong conclusions about the role of verb bias in language processing for patients with hippocampal damage and impairments in declarative (relational) memory.

4. Experiment 2

The goal of Experiment 2 was to test the use of verb bias information in patients with amnesia and healthy comparison participants using a more highly powered design. While the use of real objects and a physical display in Experiment 1 allowed for a close replication of Snedeker and Trueswell (2004) in this population, in Experiment 2 we leveraged

the efficiency of a computer-based display to substantially increase the number of trials.

4.1. Participants

Patients 1846, 2563, and 1951 participated in Experiment 2 and were 58.3 years old and had 15.3 years of education, on average, at the time of data collection. 1846 and 2563 had also participated in Experiment 1, one year and eleven months prior and two years and four months prior, respectively. The three demographically matched healthy comparison participants were 59.3 years old and had 16.3 years of education, on average. Two of the comparison participants had previously participated in Experiment 1.

4.2. Design and procedure

The experimental design and materials were adapted from Experiment 1 in Ryskin et al. (2017a), which consisted of a computerized version of Snedeker and Trueswell (2004). Participants were tested one at a time, and were seated at a computer that was connected to an Eyelink-1000 desktop-mounted eye-tracker sampling at 1000 Hz. Stimulus presentation was controlled using Matlab’s Psychophysics Toolbox 3 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). On each trial, images of the critical objects appeared on the screen, one at a time, as an auditory description played from the computer speakers over the open sound field (e.g., “Here’s a duck, a hat, another hat, a sponge, a bird, a sponge.”). Every display contained a target animal (e.g. a duck wearing a mini-hat) and a distractor animal (e.g. a bird holding a mini-sponge), as well as a target instrument (e.g. a hat) and a distractor instrument (e.g. a sponge), which were large versions of those inanimate objects (see Fig. 5). One second after the last picture appeared on the screen, participants heard an instruction, such as “Pet the duck with the hat.” The two animals on the screen were always of different types, so that there was always only one possible candidate in the display for the target noun.

For each instruction, participants were asked to act out the content of the instruction by clicking on the relevant objects and animals. Critically, the instruction in this context is globally ambiguous and the *with*-phrase could be given an instrument interpretation or a modifier interpretation. For example, to act out an instrument interpretation, a participant might pick up (click and drag) the picture of the hat and drag it over to the duck and motion the hat over the duck. To act out a modifier interpretation, the participant might simply motion the mouse over the picture of the duck that has the hat. The feasibility and naturalness of these actions were vetted in an earlier study with a young adult sample (Ryskin et al., 2017a); the present sample of participants similarly had no difficulty following the instructions using the computer interface. Participants’ eye movements were recorded from when the instruction started to when they proceeded to the next trial.

Each participant was tested in six sessions.² Each session consisted of 81 trials and lasted approximately 30 min. The 81 trials consisted of three practice trials (always the first three trials), 24 filler trials, and 54 critical trials. This experimental design generated 972 critical trials per group (3 participants x 54 critical items x 6 sessions), offering substantially more power compared to Experiment 1 (which generated a maximum of 288 critical items per group). On critical trials, participants heard instructions ending in an ambiguous *with* prepositional phrase. One third of the critical sentences (18 trials) contained modifier-biased verbs (e.g., cuddle, hug), another third contained instrument-biased verbs (e.g., hit, poke), and the last third contained equi-biased verbs (e.g., feel, locate). On filler trials, neither a modifier, nor an instrument interpretation was plausible (e.g., “Make the animals

² Most sessions were only a few minutes apart. Four sessions had a 1-day lag. Two sessions had a 7-day lag. Two sessions had a longer lag (20 days and 165 days).

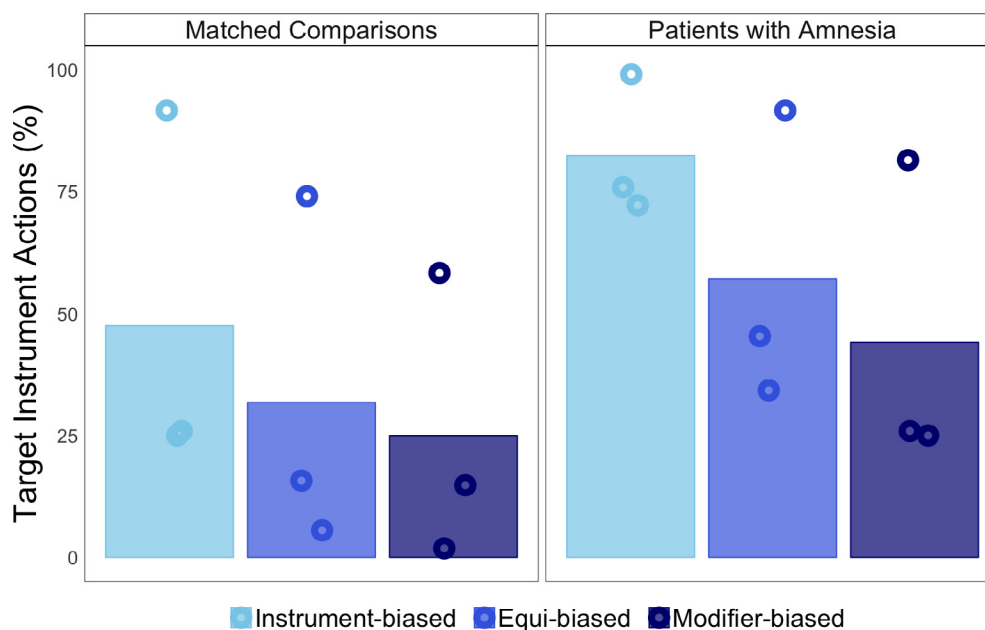


Fig. 6. Experiment 2: Proportion of initial target instrument-directed actions in three conditions (modifier-biased, equi-biased, and instrument-biased) for persons with amnesia and matched comparison participants. Performance of individual participants is indicated by the circles.

wrestle.”). Filler and critical trials were intermixed and ordered randomly for each participant.

4.2.1. Materials

The verbs used in the critical trials were selected based on the norming study reported in Ryskin et al. (2017a) and many of them overlapped with the verbs used in Experiment 1, and Snedeker and Trueswell (2004). The verbs were grouped into three categories based on whether they were modifier-biased (9 verbs), instrument-biased (9 verbs) or equi-biased (9 verbs). Each verb was presented twice within a session, each time with a different animal and a different instrument/modifier. The visual stimuli were colorized images (mostly photos and some drawings) selected to provide the clearest possible depiction of each referent. Two lists were made with different pairings of verbs (e.g., pet) with the animals and instruments (e.g., duck-hat or duck-sponge). Across the six sessions, participants alternated between the two lists.

4.3. Results

4.3.1. Actions

As a measure of participants’ behavior, we recorded which object in the display they clicked on first. Critically, to act out an instrument action, participants would need to first click the instrument in order to then drag and motion it over the target animal (see Ryskin, et al., 2017a). Participants appeared to be more likely to click on the target instrument first in the instrument-biased condition, compared to the equi-biased condition, and least of all in the modifier-biased condition (Fig. 6). Overall, patients showed numerically higher rates of target instrument clicks than controls.

Clicking behavior was analyzed using mixed-effects logistic regression. The dependent measure was whether the first click was on the target instrument or not. The model included random intercepts for participants and items, as well as random by-participant slopes for verb bias condition and random by-item slopes for participant group. Verb bias condition and participant groups were coded in the same way as in Experiment 1. The full set of parameter estimates is reported in appendix Table B1. Participants clicked on the target instrument less ($b = -1.88$, $SE = 0.36$, $z = -5.27$, $p < 0.001$) in the equi-biased and modifier-biased conditions compared to the instrument-biased condition. Participants also clicked on the target instrument less ($b = -0.75$,

$SE = 0.35$, $z = -2.18$, $p = 0.03$) in the modifier-biased condition compared to the equi-biased condition. There was no main effect of participant group ($b = 1.88$, $SE = 1.39$, $z = 1.35$, $p = 0.18$) and verb bias condition did not interact with participant group (Contrast 1: $b = -0.77$, $SE = 0.57$, $z = -1.35$, $p = 0.18$; Contrast 2: $b = -0.47$, $SE = 0.50$, $z = -0.94$, $p = 0.35$). The verb bias effect is robust across halves of the experiment (see Supplemental Fig. S2).

4.3.2. Eye-movements

The plot of fixations over time (Fig. 7) is consistent with Snedeker and Trueswell’s pattern of results and replicates Experiment 1 of Ryskin et al. (2017a). Both participant groups make more fixations to the target animal when the verb is modifier-biased than when it is equi-biased, and the instrument-biased verbs elicit the fewest fixations to the target. The reverse pattern is observed for fixations to the target instrument. The overall proportion of fixations to the target animal is lower in the amnesic group and the overall proportion of fixations to the target instrument is higher.

We analyzed the gaze data in three time windows in order to capture eye-movements elicited during both early and later portions of the sentence. All time windows were offset by 200 ms to account for the time needed to program and launch an eye movement. The first time window started at the onset of the verb (e.g., *Pet* in *Pet the duck with the hat*) and ended at the onset of the first noun (e.g., *duck*). The average duration of the first time window was 732 ms. The second time window began at the onset of the first noun and ended at the onset of the second noun (e.g., *hat*). The average duration of the second time window was 994 ms. The third time window started at the onset of the second noun and ended 1500 ms later (the maximum duration of the second noun was 1421 milliseconds³).

We fit mixed-effects linear regression models predicting eye fixations from participant group and verb bias condition, across the three time windows of interest. The dependent variable for these analyses was the same as in Experiment 1, a measure of Target Animal Advantage: proportion of fixations to the target animal minus the

³ The time windows in Experiment 2 are longer than Experiment 1 because they were recorded by different speakers on separate occasions. The additional time to capture eye-fixations in Experiment 2 may contribute to the differences in results between Experiment 1 and 2.

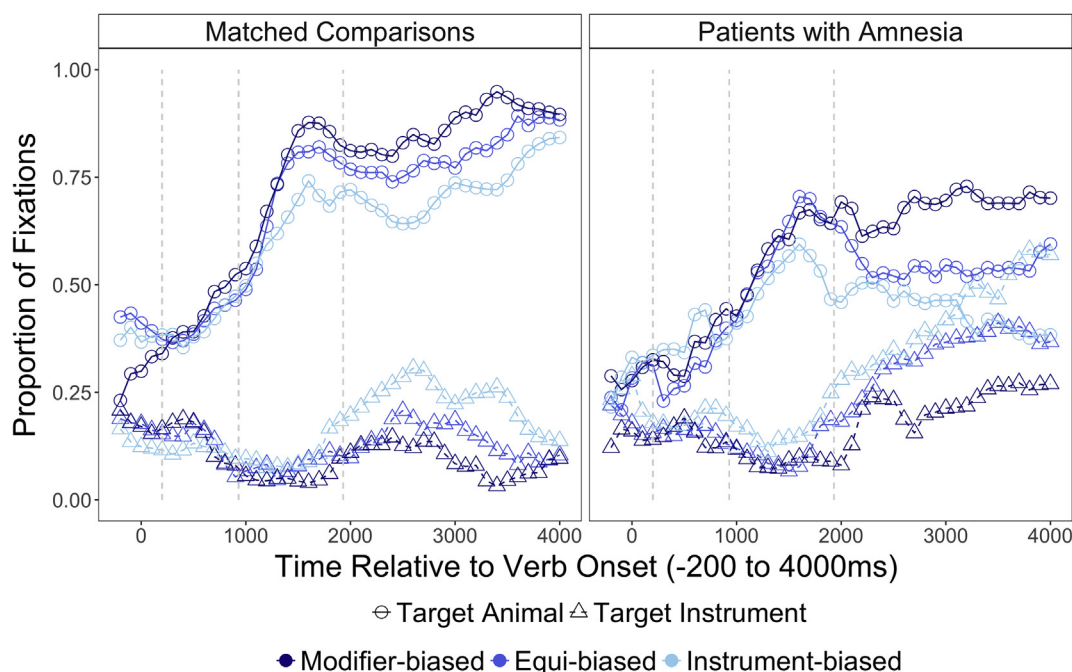


Fig. 7. Experiment 2: Proportion of gaze fixations in three conditions (modifier-biased, equi-biased, and instrument-biased) over time for persons with amnesia and demographically-matched comparison participants (graphs for each individual available in [Supplemental Material S3](#)). (Dashed lines indicate average beginnings of the three time windows used for analysis.)

proportion of fixations to the target instrument, with an empirical logit transformation as before. The model included random intercepts for participants and items, as well as random by-participant slopes for verb bias condition, time window, and their interaction and random by-item slopes for participant group, time window, and their interaction (this was the maximal random effect structure justified by the design). Verb bias condition was entered as a pair of weighted⁴ orthogonal contrast codes as in Experiment 1. The first contrast compared the instrument-biased condition (-0.68) to the average of the equi-biased (0.32) and modifier-biased (0.32) conditions. The second contrast compared the equi-biased (-0.51) condition to the modifier-biased (0.49) condition. Participant group was deviation coded (comparisons: -0.5 , patients: 0.5). Time window was Helmert coded (Contrast 1: time window 1 = -0.66 ; time window 2 = 0.33 , time window 3 = 0.33 ; Contrast 2: time window 1 = 0 ; time window 2 = -0.5 , time window 3 = 0.5). The fixed-effect parameters from these models are summarized in appendix [Table B2](#).

Across all time windows and both participant groups, the first verb bias contrast (instrument- vs. equi- and modifier-biased verbs) significantly predicted Target Animal Advantage ($b = 0.27$, $SE = 0.09$, $t = 3.01$, $p = 0.01$), such that there was a larger Target Animal Advantage for the equi- and modifier-biased verbs compared to instrument-biased verbs. The second verb bias contrast marginally predicted Target Animal Advantage ($b = 0.18$, $SE = 0.09$, $t = 2.01$, $p = 0.06$), such that Target Animal Advantage was larger for modifier-biased verbs relative to equi-biased verbs. There was also a significant effect of the first time-window contrast ($b = 0.38$, $SE = 0.12$, $t = 3.15$, $p = 0.03$), such that the target animal advantage was larger in the second and third windows, relative to the first. The first time window contrast also marginally interacted with the first verb bias contrast ($b = 0.21$, $SE = 0.11$, $t = 1.93$, $p = 0.07$) and the second time window contrast marginally interacted with the second verb bias contrast ($b = 0.28$, $SE = 0.13$, $t = 2.09$, $p = 0.07$). To further explore these interactions, we fit separate models for each of the time windows

(appendix [Table B3](#)).

In the first time window (*Pet...*), there were no significant effects of verb bias (Contrast 1: $b = 0.11$, $SE = 0.11$, $t = 0.99$, $p = 0.36$; Contrast 2: $b = 0.11$, $SE = 0.12$, $t = 0.92$, $p = 0.37$) or participant group ($b = -0.15$, $SE = 0.15$, $t = -1.01$, $p = 0.36$). In the second time window (*duck...*), Target Animal Advantage was larger ($b = 0.23$, $SE = 0.08$, $t = 2.84$, $p = 0.01$) in the equi-biased and modifier-biased conditions compared to the instrument-biased condition. The equi-biased and modifier-biased conditions were not significantly different during the second time window ($b = 0.03$, $SE = 0.10$, $t = 0.33$, $p = 0.75$), nor was there a main effect of participant group ($b = -0.32$, $SE = 0.21$, $t = -1.52$, $p = 0.20$). In the third time window (*hat...*), Target Animal Advantage was larger in the equi-biased and modifier-biased conditions compared to the instrument-biased condition ($b = 0.75$, $SE = 0.18$, $t = 3.16$, $p = 0.01$) and in the modifier-biased condition compared to the equi-biased condition ($b = 0.32$, $SE = 0.13$, $t = 2.52$, $p = 0.02$). There was no main effect of participant group ($b = -0.52$, $SE = 0.35$, $t = -1.48$, $p = 0.21$). Critically, across all three time windows, the verb bias condition did not significantly interact with participant group (Time window 3 Contrast 1: $b = -0.11$, $SE = 0.23$, $t = -0.49$, $p = 0.64$; Contrast 2: $b = 0.10$, $SE = 0.22$, $t = 0.45$, $p = 0.66$).

4.4. Discussion

The eye-tracking and offline behavioral measures in this experiment provide clear evidence that patients with hippocampal amnesia, as well as healthy matched comparison participants, make use of verb bias information when resolving global syntactic attachment ambiguity. The fact that these participants were successful suggests that the hippocampal dependent declarative (relational) memory system is not necessary for accessing previously acquired information about the likelihood of co-occurrence of lexical items with syntactic structures during online language comprehension.

⁴ Coding is weighted by the number of trials in each condition (see [Appendix B](#) for number of observations).

5. Experiment 3

The goal of Experiment 3 is to examine whether patients with amnesia and demographically-matched healthy older adults can dynamically update their representations of a verb's bias when exposed to new co-occurrence information between verbs and structures. Ryskin et al. (2017a; 2017b; 2018) found that young adults do update biases of originally equi-biased verbs after exposure to new evidence about the co-occurrences of those verbs with instrument or modifier structures. For example, after repeated exposure to *feel* paired with a modifier structure (e.g., “Which animal should you feel? I know, you should feel the duck with the hat.”) and *rub* with an instrument structure (e.g., “What should you use to rub the bunny? I know, you should rub the bunny with the brush.”), young adult listeners were more likely to interpret *feel* as a modifier-biased verb and *rub* as an instrument-biased verb for ambiguity resolution within a single 90-minute session. This verb-specific adaptation effect was revealed by an increased preference for the structure-appropriate item in the display (e.g., the target animal for *feel* and the target instrument for *rub*) during the online interpretation of the ambiguous *-with* phrase.

5.1. Participants

Patients 1846, 2563, and 1951 participated in Experiment 3 and were 59.3 years old and had 16.0 years of education, on average, at the time of data collection. All three had previously participated in Experiment 2. 1846 and 2563 had previously participated in Experiment 1 as well. The three demographically matched healthy comparison participants were 59.0 years old and had 16.7 years of education, on average.

5.2. Design & procedure

The design and procedure of this experiment were identical to Experiment 2 in Ryskin et al. (2017a), except that the pairings of verbs with structures were arbitrary but held constant across participants (e.g., *rub* was modifier-trained for all participants) in order to reduce item-specific variability. In contrast, half of the young adult participants in Ryskin et al., experienced *feel* paired with the modifier structure and the other half experienced *feel* paired with the instrument structure and vice versa for *clean*. Additionally, while young adults in Ryskin et al. were exposed to 163 trials over the course of a 90-minute session, each participant in the present study was exposed to 1280 trials over the course of 8 sessions on average. In this way, the 3 participants (per group) contributed as much data as 24 undergraduate participants in Ryskin et al.'s study. Experimental sessions were scheduled at the convenience of participants, with each session lasting approximately 30 min, and the delay between sessions ranged from 5 min to 77 days (Mean = 1.4 days, Median = 0 days). The pairings between verbs and structures (e.g., *feel*-modifier, *clean*-instrument) was constant across all sessions.

As in Experiment 2, participants listened to pre-recorded speech while looking at a display with pictures of animals and objects. Participants then used the computer mouse to act out the actions being described in the audio instructions. In contrast to Experiment 2, but following Ryskin et al. (2017a), critical trials were divided into two types: unambiguous training and ambiguous testing trials, which were pseudo-randomly intermixed.

On training trials, the audio and visual stimuli were designed to lead to an unambiguous interpretation of the syntactic structure. Importantly, the large inanimate objects were different from the small objects alongside the target and distractor animals (Fig. 8a). On *instrument training* trials, participants first heard an unambiguous instrument setup sentence, such as, “Hmm, what should you use to rub the bunny?” Then they heard the critical instruction, for example, “I know! You should rub the bunny with the bottle.” The visual display was

designed to elicit an instrument interpretation; it contained a bottle and a bunny that were in separate quadrants, and two other unrelated items.

On *modifier training* trials, participants first heard an unambiguous modifier setup sentence, such as, “Hmm, what animal should you rub?” Then they heard the critical instruction, for example, “I know! You should rub the bunny with the sponge.” The visual display contained a bunny attached to a sponge and three other unrelated items, and was designed to elicit a modifier interpretation.

On *test* trials, the audio and visual stimuli were globally ambiguous with respect to which interpretation should be used. Participants first heard an ambiguous setup sentence, “Hmm, what should you do now?”. Then participants heard the critical instruction, for example, “I know! You should rub the duck with the hat.” The setup of the visual displays was identical to those of Experiment 2, where the small version of the target instrument is attached to the target animal and the large version is presented in a separate quadrant (Fig. 8b). Thus, the visual display did not bias the listeners towards either instrument or modifier interpretation. In the test trials, the verbs were paired with entirely new animals and objects that had not been shown in the training trials.

Each participant was tested in eight sessions. One testing session consisted of four blocks. Each block lasted 20 min and contained 4 unambiguous training trials per verb, and 2 ambiguous test trials per verb, for a total of 24 critical trials per block, intermixed with 16 filler trials. The order of trials within a block was randomized for each participant. Across the 8 sessions, each participant experienced a total of 1280 trials: 512 filler trials intermixed with 768 critical trials (512 training and 256 test). An additional 3 trials were practice trials at the beginning of the first session. The experimenter also had the option to re-run the 3 practice trials at the beginning of any block (because sessions were sometimes many days apart and participants could forget what the task consisted of).

5.2.1. Materials

Audio and picture stimuli were identical to Ryskin et al. (2017a; Experiment 2). Each participant was trained on eight initially equi-biased verbs; four were randomly chosen to be instrument-trained (*clean*, *hug*, *pinch*, *squeeze*) and four were modifier-trained (*cuddle*, *feel*, *knock on*, *rub*). Each block contained four of the critical verbs (two modifier-trained and two instrument-trained). The set of four verbs being trained and tested alternated from block to block. Two lists were constructed in order to counterbalance pairings of verbs with sets of animals and objects (*rub* could go with bunny-feather in one list and duck-hat in the other). This was done to avoid any learning of contingency between verbs and animals or instruments. The eight sessions alternated between these two lists. Critically, the pairings between verbs and structure (e.g., *feel* is paired with modifier structure) were identical across lists, such that the same verb biases were being trained across all 8 sessions and across all participants. This was done in order to minimize the variability between participants; counterbalancing is essential in most experimental designs but can reduce the signal to noise ratio in experiments with small sample sizes.

Filler trials varied in their format, but always included verbs that were not used on critical trials and never contained a modifier-instrument ambiguity. One third of fillers involved an animal interacting with an instrument (e.g., “What should the elephant smell? I know! Have the elephant smell the flower.”). One third involved just an animal (e.g., “Which animal should go in a circle? I know! Drag the squirrel in a circle.”). The last third of filler trials were meant to be very different from the critical trials and involved instruments interacting with instruments (e.g., “Hmm, what should you do now? Put the lollipop beside the straw.”), instruments alone (e.g., “What should you do now? Wave the flag.”), or animals interacting with animals (e.g., “What should you do now? Make the squirrel kiss the hippo.”).

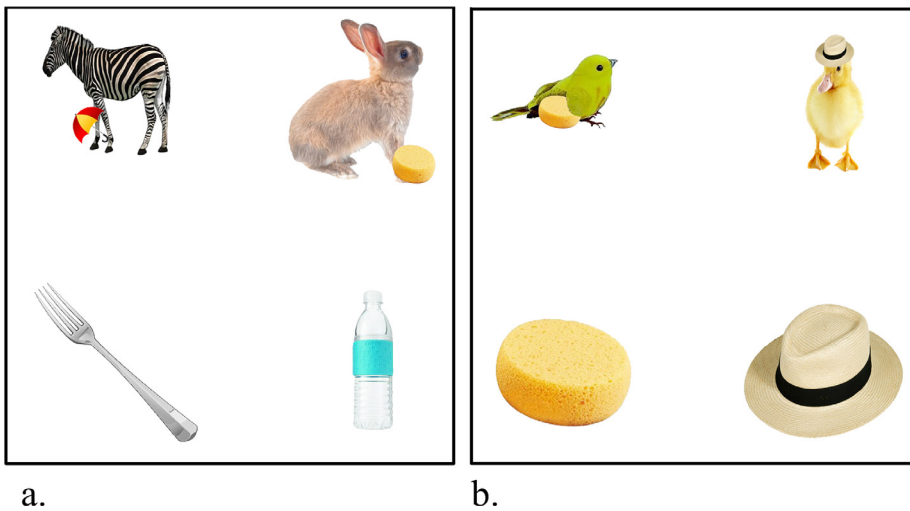


Fig. 8. Experiment 3: Displays for training and test trials. (a) For an instrument training trial, this display would be paired with an instruction such as “I know! You should rub the bunny with the bottle.” For a modifier training trial, the same display would be paired with an instruction such as “I know! You should rub the bunny with the sponge.” (b) Ambiguous test trials paired with an instruction such as “I know! You should rub the duck with the hat.”

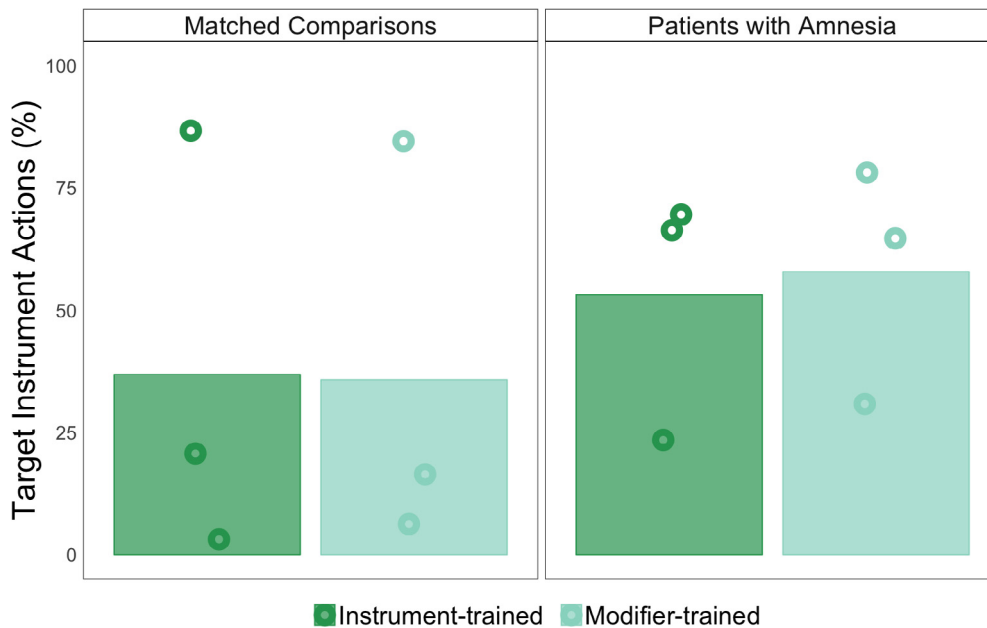


Fig. 9. Experiment 3: Proportion of initial target instrument-directed actions in two conditions (modifier-trained and instrument-trained) for persons with amnesia and matched comparison participants. Circles indicate performance of individual participants.

5.3. Results

5.3.1. Actions

As in Experiments 1 and 2, we recorded which object participants clicked on first. Participants in both groups clicked first on the target instrument equally across conditions (Fig. 9).

Clicking behavior was analyzed using mixed-effects logistic regression. The dependent measure was whether the first click was on the target instrument or not. Training condition and participant group were entered as deviation coded contrasts. Random intercepts for participants and items were included, as well as random by-participant slopes for training condition and by-item slopes for group. The full set of parameter estimates is reported in appendix Table C1. Participants’ clicks on the target instrument did not vary significantly by training condition ($b = -0.12, SE = 0.18, z = -0.69, p = 0.49$) or participant group ($b = -1.08, SE = 1.28, z = -0.84, p = 0.40$; Verb bias condition by participant group interaction: $b = 0.24, SE = 0.31, z = 0.79, p = 0.43$).

In a post-hoc analysis, we examined the possibility that a training effect in the action data could have been masked by changes over time.

Fig. 10 plots the target instrument clicks in each training condition across the 32 blocks; there was no evidence that responses changed as the sessions progressed. When centered session order is included as a predictor it does not significantly predict clicking behavior ($z = -0.02, p = 0.98$) or interact significantly with condition ($z = -1.54, p = 0.12$). There is a significant interaction between order and participant group ($b = -0.03, SE = 0.02, z = -1.98, p < 0.05$), such that patients click more on the target instrument over the course of the sessions but comparisons do not. However, the three-way interaction between condition, participant group, and order is not significant ($z = -0.88, p = 0.38$; see appendix Table C2 for full set of parameter estimates).

5.3.2. Eye-movements

The plots of fixations over time (Fig. 11) do not reveal any differences between training conditions in fixations to the target animal or the target instrument. This pattern suggests that neither patients with amnesia nor their matched healthy comparison participants learned associations between verbs and syntactic attachments. As in Experiment 2, amnesic patients appear to be less likely to fixate the target animal

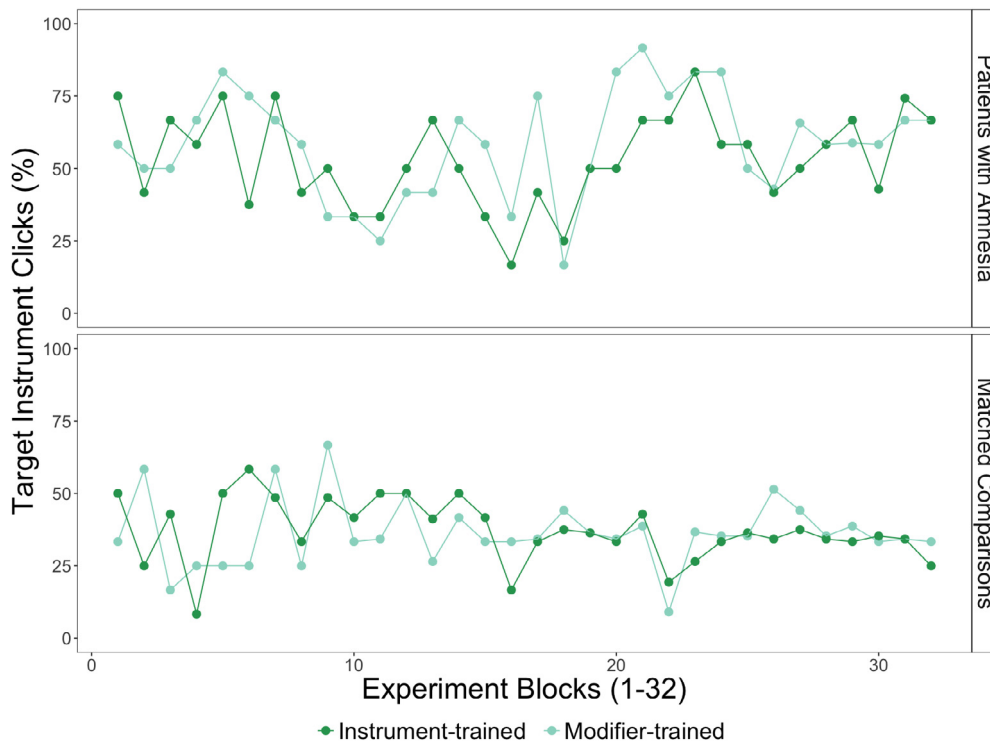


Fig. 10. Experiment 3: Proportion of target instrument clicks by training condition (instrument-trained vs. modifier-trained) across the 32 testing blocks for patients and comparison participants.

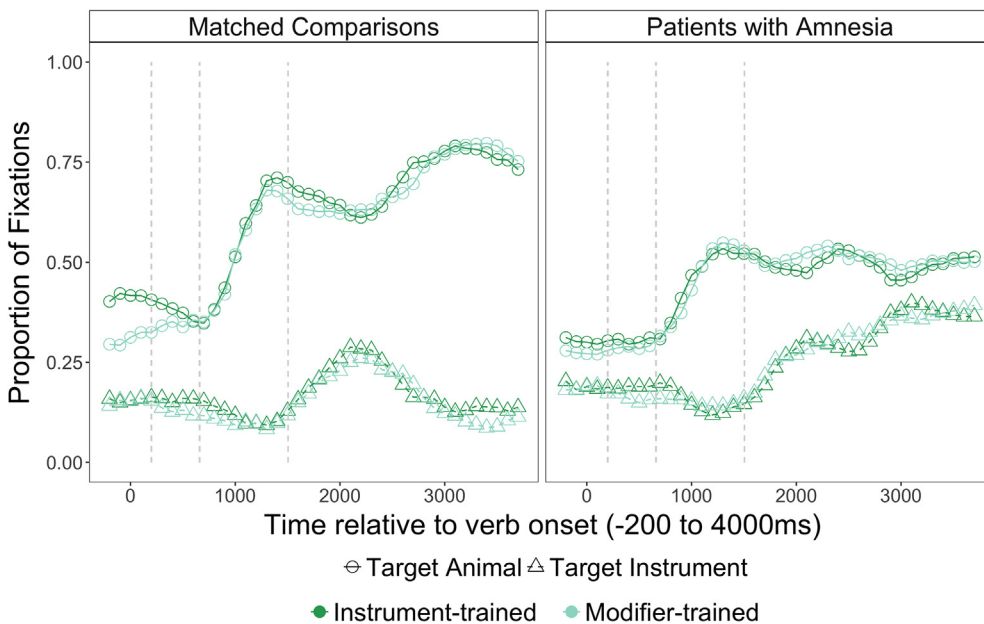


Fig. 11. Experiment 3: Proportion of gaze fixations in two conditions (modifier-trained and instrument-trained) over time for persons with amnesia and matched comparison participants (graphs for each individual available in [Supplemental Material S4](#)). (Dashed lines indicate average beginnings of the three time windows used for analysis.)

and more likely to fixate the target instrument overall, relative to the comparison participants.⁵

We analyzed the data in the same three time windows as in

⁵ One speculation about why comparison participants look more at the Target Animal than the Target Instrument has to do with the fact that selecting the target instrument leads to a longer trial duration than selecting the target animal immediately, because it requires that the participant then drag the target instrument over to the target animal. Thus, as participants become more eager to complete the experiment, they become less likely to use the instrument (see [Figs. 9 and 10](#)). Amnesic participants, on the other hand, may have less recollection of how long they have been engaged in the experiment and therefore are less likely to adopt this strategy.

Experiment 2. The first time window started at the onset of the verb (e.g., *rub*) and ended at the onset of the first noun (e.g., *duck*). The average duration of the first time window was 462 ms. The second time window began at the onset of the first noun and ended at the onset of the second noun (e.g., *hat*). The average duration of the second time window was 843 ms. The third time window started at the onset of the second noun and ended 1500 ms later.⁶

⁶ The time windows are the same as in Experiment 2 in [Ryskin et al. \(2017a\)](#). The first two time windows in Experiment 3 are shorter in duration than their analogs in the present Experiment 2, because stimuli for the two experiments were recorded separately

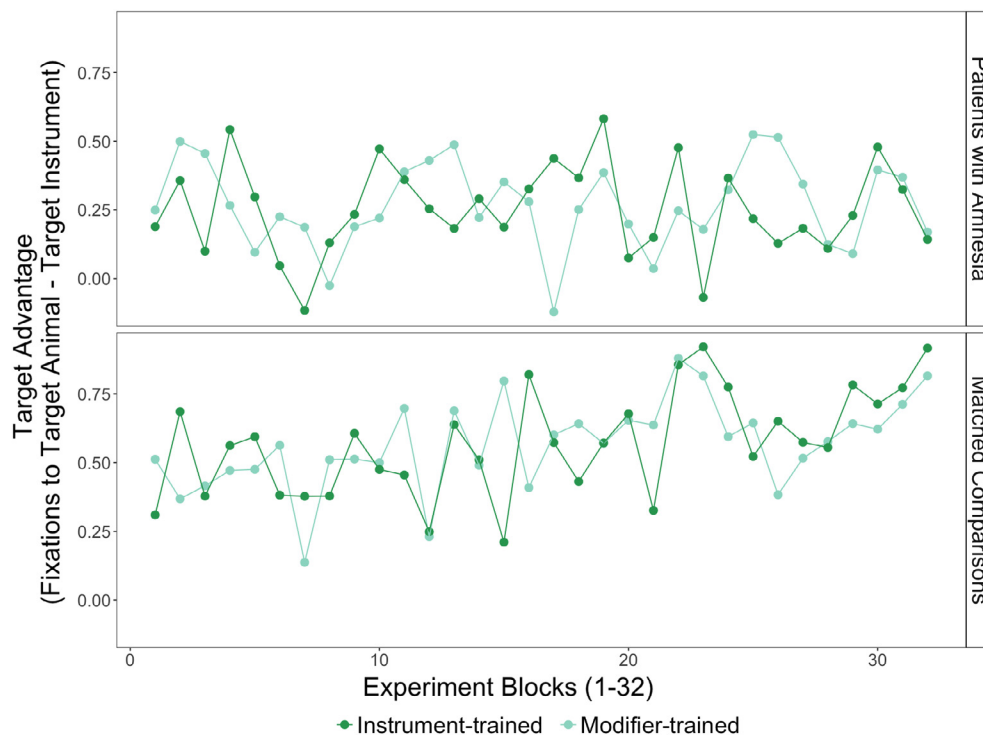


Fig. 12. Experiment 3: Target Animal Advantage by training condition (instrument-trained vs. modifier-trained) across the 32 testing blocks for patients and comparison participants.

We fit a mixed-effect linear regression model predicting eye fixations from participant group and training condition, across the three time windows of interest. The dependent variable for these analyses was Target Animal Advantage computed in the same way as in Experiments 1 and 2. The model included random intercepts for participants and items, as well as random by-participant slopes for training condition, time window, and their interaction and random by-item slopes for participant group, time window, and their interaction (this was the maximal random effect structure justified by the design). Training condition was entered as a deviation coded contrast: modifier training condition (-0.50) vs. instrument training condition (0.50), as was participant group (patients: -0.50 , comparisons: 0.50). Time window was Helmert coded (Contrast 1: time window 1 = -0.66 ; time window 2 = 0.33 , time window 3 = 0.33 ; Contrast 2: time window 1 = 0 ; time window 2 = -0.5 , time window 3 = 0.5). The parameter estimates from this model are reported in full in appendix Table C3. There was a marginal effect of time window, such that the Target Animal Advantage was smaller in the first time window relative to the latter two ($b = 0.23$, $SE = 0.11$, $t = 2.13$, $p = 0.10$). There were no significant effects of training condition ($b = 0.00$, $SE = 0.03$, $t = -0.13$, $p = 0.90$) or participant group ($b = 0.19$, $SE = 0.11$, $t = 1.79$, $p = 0.15$) and no interactions between participant group, training condition, and time window ($t_s < 0.70$, $p_s > 0.50$).

In a post-hoc analysis, we examined the possibility that a training effect could have been masked by changes over the duration of the experiment. Fig. 12 plots the Target Animal Advantage in the third time window for each training condition, across the 32 blocks. These plots do not suggest a change in the condition effect on responses as the sessions progressed. When centered block order is included as a predictor, there was no main effect of order ($t = 0.91$, $p = 0.41$) and

(footnote continued)

by different speakers (both male). The critical sentences in the present Experiment 3 were also embedded within a preamble, e.g., “I know...”, which increased the speech rate of the critical sentence itself.

critically, the three-way interaction between condition, participant group, and order was not significant ($t = 0.92$, $p = 0.41$; see appendix Table C4 for full set of parameter estimates).

The absence of a training condition effect in the comparison group is surprising given the significant training effect observed with young adult participants in an identical experimental design (Ryskin et al., 2017a, 2017b). Note, however, that while the healthy comparison participants in the current experiment, like the participants in Ryskin et al. (2017a, 2017b) do not have profound declarative memory impairment, and thus do likely have grossly intact hippocampal structures, the comparison participants in the present study are much older because the comparison participants are age-matched to the amnesic patients who range in age from 55 to 63. The participants in Ryskin et al.’s experiment were undergraduate students at University of Illinois at Urbana-Champaign; while data on age were not collected from these participants, they likely ranged in age from 18 to 23. In order to better understand whether this difference between the experiments is meaningful, we compare the results of the current experiment with the analogous data from undergraduate-age participants in a post-hoc analysis. We used a subset of data from the younger adults (a random set of 24 participants with 32 test trials each) that was equivalent in size to the comparison (3 participants with 256 test trials each) and patient samples (1 participant with 248 test trials and 2 participants with 256 test trials each). Participant group was entered as a pair of weighted orthogonal contrast codes. The first contrast compared the young adults (-0.67) to the average of the comparison participants (0.33) and patients (0.33). The second contrast compared the comparison participants (-0.50) to the patients (0.49). A logistic mixed-effects model analysis of first clicks on the target instrument (see appendix Table D1 for model estimates and D2 for a figure) reveals a main effect of training condition ($z = 2.81$, $p = 0.005$) and significant interaction between training condition and the first group contrast (young adults vs. comparison participants and patients; $z = -3.16$, $p = 0.002$), but no interaction between training condition and the second group contrast (comparison participants vs. patients; $z = -1.04$, $p = 0.30$). A linear

mixed-effects model analysis of Target Animal Advantage in the third time-window (see appendix Table D3) reveals a marginal interaction between training condition and the first group contrast ($t = 2.05$, $p = 0.08$) but no interaction between training condition and the second group contrast ($t = -0.16$, $p = 0.88$). These results tentatively suggest that the absence of a training effect in both the comparison and patient groups is not due to lack of power; we observe significant training effects in a similarly-sized sample of young adult participants. Nonetheless, it is impossible to say, at this point, how the slight differences in experimental design or individual differences may have impacted the power of the experiment.

5.4. Discussion

Participants did not select the target instrument differentially depending on training condition, nor did their fixation patterns differ between training conditions. This was true for both amnesic patients and age-matched comparison participants. In contrast to findings from an earlier study of healthy young adults, neither patients with hippocampal lesions nor healthy older adult comparison participants appear to learn novel verb-structure bindings from exposure.

6. General discussion

In three experiments, we explored the use of verb bias during online language processing in patients with amnesia and demographically matched healthy comparison participants. Experiments 1 and 2 examined whether patients with hippocampal damage were able to use *previously acquired* verb bias information to guide processing in the moment, while Experiment 3 examined whether the hippocampal relational memory system supports the updating of verb bias information based on recent linguistic experience. Taken together, Experiments 1 and 2 provided clear evidence that the ability to make use of verb bias information to guide online interpretation of globally ambiguous syntactic structures, based on information acquired prior to the onset of amnesia, does not rely on the hippocampus. Both patients with amnesia and matched comparison participants select the target instrument more when the given verb is instrument-biased than when it is equi-biased and least when it is modifier-biased. Conversely, they fixate the target animal most when the verb is modifier-biased and least when it is instrument-biased. Experiment 3 demonstrates that patients with hippocampal damage fail to update verb bias information based on recent linguistic experience. While amnesic patient performance is markedly different from healthy undergraduates (Ryskin et al., 2017a, 2017b), healthy older adults in this study *also* demonstrated a lack of updating of verb bias information.

6.1. The role of the hippocampus in syntactic processing

Results of Experiments 1 and 2 are consistent with earlier work in patients with hippocampal amnesia demonstrating preserved syntactic processing in offline tasks. For example, patients with hippocampal amnesia demonstrate intact syntactic priming in the absence of recognition memory for the primes themselves (Ferreira et al., 2008; Heyselaar, Segaert, Walvoort, Kessels, & Hagoort, 2017), are able to identify syntactic ambiguity in offline tasks (Schmolck et al., 2000; although note impaired performance in patients with damage extending into temporal cortex, MacKay et al., 1998), and demonstrate intact artificial grammar learning (Knowlton et al., 1992). The current study builds on these previous findings to demonstrate that patients with hippocampal amnesia are able to successfully make use of this previously acquired syntactic information *in the moment*. This distinction is important given that other clinical populations have been shown to demonstrate preserved performance in offline tasks alongside disrupted processing in the moment (e.g., McMurray, Samelson, Lee, & Tomblin, 2010). In the domain of language, earlier work from our group reports

deficits in amnesia during the online processing of language, particularly when information must be integrated across sentences, including pronoun resolution processes (Kurczek et al., 2013), and perspective-taking processes that rely on a prior record of the discourse (Rubin et al., 2011). These findings motivate arguments that hippocampal declarative memory may play a role in the online processing of language (Duff & Brown-Schmidt, 2012, 2017; Brown-Schmidt & Duff, 2016). Taken together, results from this study alongside the Kurczek et al. results suggest that the hippocampus is not critical for *all* online language processing, per se. In contrast, we propose that the hippocampus contributes to online language processing when relational memory demands are high. In Kurczek, et al.'s (2013) study of referential processing, patients with hippocampal amnesia were nearly at chance in linking an ambiguous pronoun to a prior referent in a story. This process requires significant relational memory demands, including encoding of the temporal order of the referents and re-instantiation of these representations upon onset of the pronoun. In Experiments 1–2 of the current study, there are no new explicit relational memory demands: participants draw upon their *previously acquired* verb bias knowledge. For patients with amnesia, this information was acquired prior to the onset of their amnesic condition and thus was available to them to guide online syntactic ambiguity resolution.

A secondary aim of this research was to evaluate whether the ability to learn and then use new information about verb-structure co-occurrences is hippocampal dependent. Experiment 3 differs from 1 and 2 in that participants are required to *update* their pre-existing verb biases in the face of new linguistic information. We hypothesized that updating verb bias information based upon accumulating experience with new verb-structure co-occurrences might place demands on hippocampal relational memory due to the need to track regularities between verbs and syntactic interpretations. In Experiment 3, neither patients nor comparison participants selected the target instrument more when the verb had been associated with instrument-training than modifier-training even when clicks were examined over the course of the entire exposure. Similarly, there were no differences in fixation patterns across training conditions. In contrast, a re-analysis of a subset of the data from Ryskin et al. (2017a) shows that the training effect was present in a sample that is matched in size to the one used here, suggesting that power to detect the training effect is not at issue here. However, given the small sample size, a Type II error may be due to individual differences. In other words, it is possible that a different set of three comparison participants or patients would have demonstrated evidence of learning in this paradigm.⁷

Taking the absence of learning effects at face value, one potential interpretation is that neural or cognitive changes associated with healthy aging impact older adults' ability to update verb bias information relative to healthy undergraduates. The failure of healthy older adults to acquire new verb bias knowledge would be consistent with a growing body of work on the impact of healthy aging on multiple aspects of online language processing, such as syntactic ambiguity resolution (Payne et al., 2014), use of sentence context (Federmeier & Kutas, 2005; Federmeier, Van Petten, Schwartz, & Kutas, 2003), prediction of upcoming lexical items (Federmeier, McLennan, De Ochoa, & Kutas, 2002), and updating lexical-semantic representations on the basis of experience (Rodd et al., 2016).

An intriguing yet speculative explanation might be that patients and older comparisons both failed to demonstrate updating of verb biases due to shared hippocampal pathology. Morphological, cellular, and volumetric declines in hippocampus are hallmark in healthy aging and begin in the fifth and sixth decades of life (Fjell et al., 2013; Raz et al.,

⁷ Note however that the participants in this study are drawn from the same population as several other studies in which there are significant differences in performance between patients and comparisons, such that patients have deficits in hippocampal-dependent memory performance and comparisons do not (e.g., Kurczek et al., 2013, 2015; Warren and Duff, 2014).

2005; Walhovd et al., 2011) – the age range of the healthy participants reported here. If this interpretation were to hold, the lack of updating in individuals with amnesia and healthy older adults would be consistent with arguments that episodic memory is involved in learning of new verb-structure bindings (Kaschak & Glenberg, 2004) and the updating of existing semantic representations (Klooster & Duff, 2015), as well as evidence that the hippocampus contributes to tracking of statistical regularities (Covington et al., 2018; Schapiro et al., 2014; Turk-Browne, Scholl, Chun, & Johnson, 2009). Alternatively, it is also possible that verb biases in older adults are less malleable due to the additional decades of language exposure that cannot be outweighed by in-the-lab experiences. Further investigation is needed to understand whether and how the progressive, age-related changes in the hippocampus affect language processing.

7. Conclusion

The online resolution of syntactic ambiguity is influenced by knowledge about the statistical regularities with which particular verbs are used in one syntactic construction or another (Garnsey et al., 1997; Snedeker & Trueswell, 2004). The present research demonstrates that the ability to use probabilistic verb bias to resolve syntactic ambiguities is not dependent on the hippocampal declarative memory system. This finding (a) furthers our understanding of the memory mechanisms recruited during online syntactic processing, suggesting that relational binding is not necessary for in-the-moment use of lexically-specific

Appendix A. Experiment 1

See Tables A1 and A2

Table A1

Estimated parameters for mixed-effects models predicting clicks on the target instrument. (I = Instrument-biased, E = Equi-biased, M = Modifier-biased condition, Group = Comparisons vs. Patients). Asterisk indicates significance at alpha level of 0.05.

	Estimate	Std. Error	z-value	p-value
<i>Fixed Effects</i>				
(Intercept)	−1.484	0.728	−2.039	0.041
I vs. E & M	−3.342	0.756	−4.419	< 0.001*
E vs. M	0.744	0.969	0.768	0.442
Group	−0.626	1.339	−0.467	0.64
I vs. E & M x Group	1.145	1.045	1.095	0.274
E vs. M x Group	0.786	1.226	0.641	0.521
<i>Random Effects</i>				
(Intercept) Participant	1.801			
I vs. E & M Participant	0.916			
E vs. M Participant	1.099			
(Intercept) Verb	1.255			
Group Verb	0.852			
Observations: 572, Participants: 8, Verbs: 24				

syntactic knowledge, which may be guided by retrieval from long-term memory stores, and (b) circumscribes the nature of language impairment in patients with hippocampal damage. Furthermore, this work takes a first step towards exploring whether the lifelong updating of probabilistic verb-structure co-occurrence information is a hippocampal-demanding process. While the failure of either group to update their verb biases does not allow conclusions regarding the role of hippocampus, this surprising finding highlights the fragility of such learning processes. Whether a lifetime of linguistic exposure, age-related hippocampal atrophy, task-specific variables, or some other process contributed to this failure to learn remains an open question ripe for future inquiry.

Conflict of interest

The authors declare no conflicts of interest.

Acknowledgments

This research was supported by National Institutes of Health/ National Institute on Deafness and Other Communication Disorders Grant RO1 DC011755 to Melissa Duff and Sarah Brown-Schmidt. We would also like to thank Firmino Pinto for constructing materials used in Experiment 1 and Tatsu Shigeta and Sharice Clough for help with data collection.

Table A2

Estimated parameters for mixed-effects models predicting Target animal advantage in fixations. (I = Instrument-biased, E = Equi-biased, M = Modifier-biased condition, Group = Comparisons vs. Patients, T1 = First Time window, T2 = Second Time window, T3 = Third Time window). Asterisk indicates significance at alpha level of 0.05.

<i>Fixed Effects</i>	Estimate	Std. Error	t-value	p-value
(Intercept)	2.08	0.48	4.38	0.00
I vs. E & M	0.53	0.78	0.67	0.51
E vs. M	-0.03	0.91	-0.03	0.97
Group	0.79	0.62	1.28	0.25
T1 vs. T2 & T3	2.00	0.58	3.44	0.003*
T2 vs. T3	-0.08	0.60	-0.14	0.89
I vs. E & M x Group	-0.17	0.32	-0.52	0.60
E vs. M x Group	0.57	0.38	1.50	0.13
I vs. E & M x T1 vs. T2 & T3	0.27	0.90	0.29	0.77
E vs. M x T1 vs. T2 & T3	-0.39	1.05	-0.37	0.71
I vs. E & M x T2 vs. T3	0.76	0.73	1.04	0.31
E vs. M x T2 vs. T3	-0.52	0.84	-0.62	0.54
Group x T1 vs. T2 & T3	-0.44	0.86	-0.52	0.62
Group x T2 vs. T3	0.30	1.04	0.29	0.78
I vs. E & M x Group x T1 vs. T2 & T3	-0.58	0.68	-0.85	0.40
E vs. M x Group x T1 vs. T2 & T3	-1.23	0.80	-1.53	0.13
I vs. E & M x Group x T2 vs. T3	-0.42	0.79	-0.54	0.59
E vs. M x Group x T2 vs. T3	-0.37	0.93	-0.40	0.69
<i>Random Effects</i>	Std. Dev.			
(Intercept) Participant	0.85			
T1 vs. T2 & T3 Participant	1.12			
T2 vs. T3 Participant	1.38			
(Intercept) Verb	1.77			
T1 vs. T2 & T3 Verb	1.93			
T2 vs. T3 Verb	1.42			
Residual	3.04			
Observations: 1581, Participants: 8, Verbs: 24				

Appendix B. Experiment 2

See [Tables B1–B3](#)

Table B1

Estimated parameters for mixed-effects models predicting clicks on the target instrument. (I = Instrument-biased, E = Equi-biased, M = Modifier-biased condition, Group = Comparisons vs. Patients). Asterisk indicates significance at alpha level of 0.05.

	Estimate	Std. Error	z-value	p-value
<i>Fixed Effects</i>				
(Intercept)	0.000	0.704	0.000	1.000
I vs. E & M	-1.884	0.357	-5.272	< 0.001*
E vs. M	-0.753	0.346	-2.18	0.029*
Group	1.876	1.39	1.35	0.177
I vs. E & M x Group	-0.773	0.572	-1.35	0.177
E vs. M x Group	-0.467	0.496	-0.942	0.346
<i>Random Effects</i>				
(Intercept) Participant	1.687			
I vs. E & M Participant	0.429			
E vs. M Participant	0.124			
(Intercept) Item	0.899			
Group Item	1.019			
Observations: 1944, Participants: 6, Items: 54				

Table B2

Estimated parameters for mixed-effects models predicting Target animal advantage in fixations. (I = Instrument-biased, E = Equi-biased, M = Modifier-biased condition, Group = Comparisons vs. Patients, T1 = First Time window, T2 = Second Time window, T3 = Third Time window). Asterisk indicates significance at alpha = 0.05.

<i>Fixed Effects</i>	Estimate	Std. Error	t-value	p-value
(Intercept)	0.73	0.12	6.25	0.00*
I vs. E & M	0.27	0.09	3.01	0.01*
E vs. M	0.18	0.09	2.01	0.06 [†]
Group	-0.35	0.23	-1.55	0.19
T1 vs. T2 & T3	0.38	0.12	3.15	0.03*
T2 vs. T3	-0.16	0.11	-1.48	0.21
I vs. E & M x Group	0.03	0.16	0.18	0.86
E vs. M x Group	0.00	0.16	-0.02	0.99
I vs. E & M x T1 vs. T2 & T3	0.21	0.11	1.93	0.07 [†]
E vs. M x T1 vs. T2 & T3	0.08	0.14	0.6	0.56
I vs. E & M x T2 vs. T3	0.17	0.12	1.4	0.20
E vs. M x T2 vs. T3	0.28	0.13	2.09	0.07 [†]
Group x T1 vs. T2 & T3	-0.26	0.24	-1.11	0.33
Group x T2 vs. T3	-0.22	0.22	-1.02	0.36
I vs. E & M x Group x T1 vs. T2 & T3	-0.20	0.2	-1	0.34
E vs. M x Group x T1 vs. T2 & T3	-0.01	0.25	-0.02	0.98
I vs. E & M x Group x T2 vs. T3	-0.22	0.24	-0.94	0.38
E vs. M x Group x T2 vs. T3	0.25	0.26	0.98	0.36
<i>Random Effects</i>	Std. Dev.			
(Intercept) Participant	0.27			
I vs. E & M Participant	0.15			
E vs. M Participant	0.11			
T1 vs. T2 & T3 Participant	0.27			
T2 vs. T3 Participant	0.25			
I vs. E & M x T1 vs. T2 & T3 Participant	0.10			
E vs. M x T1 vs. T2 & T3 Participant	0.18			
I vs. E & M x T2 vs. T3 Participant	0.18			
E vs. M x T2 vs. T3 Participant	0.19			
(Intercept) Item	0.20			
Group Item	0.29			
T1 vs. T2 & T3 Item	0.19			
T2 vs. T3 Item	0.25			
Group x T1 vs. T2 & T3 Item	0.13			
Group x T2 vs. T3 Item	0.18			
Residual	1.07			
Observations: 3781, Participants: 6, Items: 54				

[†] Indicates marginally significant effects.

Table B3

Estimated parameters for mixed-effects models predicting Target animal advantage in each of the three time windows. (I = Instrument-biased, E = Equi-biased, M = Modifier-biased condition, Group = Comparisons vs. Patients). Asterisk indicates significance at alpha level of 0.05.

Time Window 1	Fixed Effects	Estimate	Std. Error	t-value	p-value
	(Intercept)	0.46	0.08	5.92	0.00*
	I vs. E & M	0.11	0.11	0.99	0.36
	E vs. M	0.11	0.12	0.92	0.37
	Group	-0.15	0.15	-1.01	0.36
	I vs. E & M x Group	0.19	0.2	0.92	0.39
	E vs. M x Group	0.00	0.21	0.00	1.00
	<i>Random Effects</i>	Std. Dev.			
	(Intercept) Participant	0.16			
	I vs. E & M Participant	0.14			
	E vs. M Participant	0.12			
	(Intercept) Item	0.16			
	Group Item	0.17			
	Residual	1.12			
Time Window 2	Fixed Effects	Estimate	Std. Error	t-value	p-value
	(Intercept)	0.92	0.11	8.49	0.00*
	I vs. E & M	0.23	0.08	2.84	0.01*
	E vs. M	0.03	0.10	0.33	0.75
	Group	-0.32	0.21	-1.52	0.20
	I vs. E & M x Group	0.10	0.13	0.75	0.46
	E vs. M x Group	-0.14	0.16	-0.87	0.39
	<i>Random Effects</i>	Std. Dev.			
	(Intercept) Participant	0.25			
	I vs. E & M Participant	0.00			
	E vs. M Participant	0.06			
	(Intercept) Item	0.17			
	Group Item	0.15			
	Residual	1.01			
Time Window 3	Fixed Effects	Estimate	Std. Error	t-value	p-value
	(Intercept)	0.75	0.18	4.27	0.01*
	I vs. E & M	0.40	0.13	3.16	0.01*
	E vs. M	0.32	0.13	2.52	0.02*
	Group	-0.52	0.35	-1.48	0.21
	I vs. E & M x Group	-0.11	0.23	-0.49	0.64
	E vs. M x Group	0.10	0.22	0.45	0.66
	<i>Random Effects</i>	Std. Dev.			
	(Intercept) Participant	0.42			
	I vs. E & M Participant	0.21			
	E vs. M Participant	0.16			
	(Intercept) Item	0.26			
	Group Item	0.36			
	Residual	1.09			

Appendix C. Experiment 3

See [Tables C1–C4](#)

Table C1

Estimated parameters from logistic mixed-effects model predicting clicks on the target instrument. (Mod = Modifier, Inst = Instrument, Group = Comparisons vs. Patients).

	Estimate	Std. Error	z-value	p-value
<i>Fixed Effects</i>				
(Intercept)	−0.286	0.644	−0.444	0.657
Mod vs. Inst -trained	−0.122	0.176	−0.694	0.488
Group	−1.08	1.284	−0.841	0.400
Mod vs. Inst x Group	0.243	0.308	0.788	0.431
<i>Random Effects</i>				
(Intercept) Participant	1.561			
Mod vs. Inst -trained Participant	0.138			
(Intercept) Item	0.353			
Group Item	0.143			
Observations: 1463, Participants: 6, Items: 64				

Table C2

Estimated parameters for mixed-effects models predicting clicks on the target instrument with session order as a predictor (Mod = Modifier, Inst = Instrument, Group = Comparisons vs. Patients, Block order ranges from 1 to 32).

	Estimate	Std. Error	z-value	p-value
<i>Fixed Effects</i>				
(Intercept)	−0.293	0.65	−0.45	0.652
Mod vs. Inst -trained	−0.135	0.18	−0.75	0.453
Group	−1.089	1.297	−0.84	0.401
Block order	0	0.008	−0.02	0.984
Mod vs. Inst -trained x Group	0.217	0.316	0.688	0.491
Mod vs. Inst -trained x Block order	−0.023	0.015	−1.542	0.123
Group x Block order	−0.03	0.015	−1.976	0.048
Mod vs. Inst -trained x Group x Block order	−0.027	0.03	−0.884	0.376
<i>Random Effects</i>				
(Intercept) Participant	1.578			
Mod vs. Inst -trained Participant	0.161			
(Intercept) Item	0.356			
Group Item	0.106			
Observations: 1463, Participants: 6, Items: 64				

Table C3

Estimated parameters for mixed-effects models predicting Target animal advantage in fixations. (Mod = Modifier, Inst = Instrument, Group = Comparisons vs. Patients, T1 = First Time window, T2 = Second Time window, T3 = Third Time window).

<i>Fixed Effects</i>	Estimate	Std. Error	t-value	p-value
(Intercept)	0.34	0.05	6.43	0.00
Mod vs. Inst -trained	0.00	0.03	-0.13	0.90
Group	0.19	0.11	1.79	0.15
T1 vs. T2 & T3	0.23	0.11	2.13	0.10 [†]
T2 vs. T3	0.00	0.16	0.02	0.98
Mod vs. Inst -trained x Group	0.00	0.07	0.02	0.99
Mod vs. Inst -trained x T1 vs. T2 & T3	0.02	0.06	0.31	0.76
Mod vs. Inst -trained x T2 vs. T3	-0.01	0.05	-0.21	0.84
Group x T1 vs. T2 & T3	0.14	0.21	0.68	0.54
Group x T2 vs. T3	0.14	0.32	0.44	0.68
Mod vs. Inst -trained x Group x T1 vs. T2 & T3	-0.02	0.10	-0.15	0.88
Mod vs. Inst -trained x Group x T2 vs. T3	0.05	0.10	0.45	0.66
<i>Random Effects</i>				
(Intercept) Participant	Std. Dev.			
Mod vs. Inst -trained Participant	0.13			
T1 vs. T2 & T3 Participant	0.06			
T2 vs. T3 Participant	0.25			
Mod vs. Inst -trained x T1 vs. T2 & T3 Participant	0.38			
Mod vs. Inst -trained x T2 vs. T3 Participant	0.08			
(Intercept) Item	0.06			
Group Item	0.12			
T1 vs. T2 & T3 Item	0.10			
T2 vs. T3 Item	0.09			
Group x T1 vs. T2 & T3 Item	0.11			
Group x T2 vs. T3 Item	0.16			
Residual	0.59			
Observations: 4507, Participants: 6, Items: 64				

[†] Indicates marginally significant result at alpha level of 0.05.

Table C4

Estimated parameters for mixed-effects models predicting Target animal advantage in the third time-window with session order as a predictor. (Mod = Modifier, Inst = Instrument, Group = Comparisons vs. Patients).

<i>Fixed Effects</i>	Estimate	Std. Error	t-value	p-value
(Intercept)	0.41	0.16	2.59	0.06
Mod vs. Inst -trained	-0.01	0.04	-0.14	0.89
Group	0.31	0.32	0.96	0.39
Block order	0.01	0.01	0.91	0.41
Mod vs. Inst -trained x Group	0.02	0.07	0.29	0.78
Mod vs. Inst -trained x Block order	0.00	0.00	0.28	0.79
Group x Block order	0.01	0.01	0.92	0.41
Mod vs. Inst -trained x Group x Block order	0.00	0.01	0.33	0.76
<i>Random Effects</i>				
(Intercept) Participant	0.39			
Mod vs. Inst -trained Participant	0.04			
Block order Participant	0.01			
Mod vs. Inst -trained x Block order Participant	0.01			
(Intercept) Item	0.39			
Group Item	0.08			
Block order Item	0.01			
Residual	0.52			
Observations: 1528, Participants: 6, Items: 64				

Appendix D. Comparison between Experiment 3 and Ryskin et al. (2017a)

See Tables D1 and D3
See Fig. D2

Table D1

Logistic mixed-effects model of first clicks to the target instrument by Condition (Mod = Modifier, Inst = Instrument) and Group (Group contrast 1: Young adults vs. Age-matched comparisons and patients, Group contrast 2: Age-matched comparisons vs. patients). Young adult data are a subset of data from Experiment 2 in Ryskin et al. (2017a). Asterisk indicates significance at alpha level of 0.05.

	Estimate	Std. Error	z-value	p-value
<i>Fixed Effects</i>				
(Intercept)	-0.22	0.44	-0.49	0.62
Mod vs. Inst -trained	0.34	0.12	2.81	0.005 *
Group contrast 1	-0.4	0.72	-0.56	0.58
Group contrast 2	1.18	1.27	0.93	0.35
Mod vs. Inst -trained x Group contrast 1	-0.78	0.25	-3.16	0.002 *
Mod vs. Inst -trained x Group contrast 2	-0.31	0.29	-1.04	0.30
<i>Random Effects</i>				
(Intercept) Participant	1.55			
Mod vs. Inst -trained Participant	0.02			
(Intercept) Item	0.56			
Group contrast 1 Item	0.74			
Group contrast 2 Item	0.2			
Observations: 2296, Participants: 30, Items: 64				

Table D3

Linear mixed-effects model of Target animal advantage by Condition (Mod = Modifier, Inst = Instrument) and Group (Group contrast 1: Young adults vs. Age-matched comparisons and patients, Group contrast 2: Age-matched comparisons vs. patients). Young adult data are a subset of data from Experiment 2 in Ryskin et al. (2017).

	Estimate	Std. Error	t-value	p-value
<i>Fixed Effects</i>				
(Intercept)	0.49	0.14	3.55	0
Mod vs. Inst -trained	-0.11	0.08	-1.39	0.21
Group contrast 1	-0.22	0.23	-0.98	0.34
Group contrast 2	-0.3	0.39	-0.77	0.45
Mod vs. Inst -trained x Group contrast 1	0.28	0.14	2.05	0.08 [†]
Mod vs. Inst -trained x Group contrast 2	-0.04	0.22	-0.16	0.88
<i>Random Effects</i>				
(Intercept) Participant	0.48			
Mod vs. Inst -trained Participant	0.25			
(Intercept) Item	0.17			
Group contrast 1 Item	0.39			
Group contrast 2 Item	0.05			
Residual	0.82			
Observations: 2279, Participants: 30, Items: 64				

[†] Indicates marginally significant result at alpha level of 0.05.

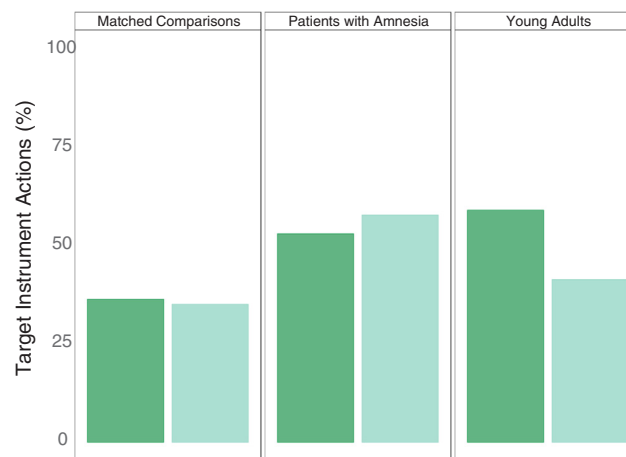


Fig. D2. Proportion of initial target instrument-directed actions in two conditions (Modifier-trained and Instrument-trained) for persons with amnesia, matched comparison participants, and young adults from Ryskin et al. (2017a). Individual participants' performance not plotted due to differences in the numbers of trials that would go into the averages for each point across groups.

Appendix E. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.bandl.2018.04.003>.

References

- Allen, J. S., Tranel, D., Bruss, J., & Damasio, H. (2006). Correlations between regional brain volumes and memory performance in amnesia. *Journal of Clinical and Experimental Neuropsychology*, 28(4), 457–476.
- Barens, M. D., Gaffan, D., & Graham, K. S. (2007). The human medial temporal lobe processes online representations of complex objects. *Neuropsychologia*, 45(13), 2963–2974. <http://dx.doi.org/10.1016/j.neuropsychologia.2007.05.023>.
- Barr, D. J. (2008). Analyzing “visual world” eyetracking data using multilevel logistic regression. *Journal of Memory and Language*, 59(4), 457–474. <http://dx.doi.org/10.1016/j.jml.2007.09.002>.
- Bates, D., Maechler, M., Bolker, B. M., & Walker, S. (2015). Fitting linear mixed-effects models using {lme4}. *Journal of Statistical Software*, 67(1), 1–48. <http://doi.org/10.18637/jss.v067.i01>.
- Blank, I., Duff, M., Brown-Schmidt, S., & Fedorenko, E. (2018). Expanding the language network: Domain-specific hippocampal recruitment during high-level linguistic processing. <https://doi.org/10.1101/091900>, in preparation.
- Boland, J. E. (1997). The Relationship between syntactic and semantic processes in sentence comprehension processes in sentence comprehension. *Language and Cognitive Processes*, 12(4), 423–484. <http://dx.doi.org/10.1080/016909697386808>.
- Boland, J. E., Tanenhaus, M. K., Garnsey, S. M., & Carlson, G. N. (1995). Verb argument structure in parsing and interpretation: Evidence from wh-questions. *Journal of Memory and Language*, 34, 774–806. <http://dx.doi.org/10.1006/jmla.1995.1034>.
- Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, 10, 433–436. <http://dx.doi.org/10.1163/156856897X00357>.
- Brown-Schmidt, S., & Duff, M. C. (2016). Memory and common ground processes in language use. *Topics in Cognitive Science*, 8, 722–736. <http://dx.doi.org/10.1111/tops.12224>.
- Buchanan, T. W., Tranel, D., & Adolphs, R. (2005). Emotional autobiographical memories in amnesic patients with medial temporal lobe damage. *Journal of Neuroscience*, 25(12), 3151–3160.
- Chang, F., Dell, G. S., & Bock, K. (2006). Becoming syntactic. *Psychological Review*, 113(2), 234–272. <http://dx.doi.org/10.1037/0033-295X.113.2.234>.
- Chang, F., Janciuskas, M., & Fitch, H. (2012). Language adaptation and learning: Getting explicit about implicit learning. *Linguistics and Language Compass*, 6(5), 259–278. <http://dx.doi.org/10.1002/inc3.337>.
- Cohen, N. J., & Eichenbaum, H. (1993). *Memory, amnesia and the hippocampal system*. Cambridge, MA: MIT Press.
- Covington, N. V., Brown-Schmidt, S., & Duff, M. C. (2018). The necessity of the hippocampus for statistical learning. *Journal of Cognitive Neuroscience*, 30(5), 680–697. http://dx.doi.org/10.1162/jocn_a.01228.
- Coyle, J. M., & Kaschak, M. P. (2008). Patterns of experience with verbs affect long-term cumulative structural priming. *Psychonomic Bulletin and Review*, 15(5), 967–970. <http://dx.doi.org/10.3758/PBR.15.5.967>.
- Davachi, L. (2006). Item, context and relational episodic encoding in humans. *Current Opinion in Neurobiology*, 16(6), 693–700. <http://dx.doi.org/10.1016/j.conb.2006.10.012>.
- Duff, M. C. & Brown-Schmidt, S. (2017). Hippocampal contributions to language use and processing. In D. Hannula & M. C. Duff (Eds.), *The hippocampus from cells to systems: Structure, connectivity, and functional contributions to memory and flexible cognition*. (pp. 503–536). Springer International Publishing.
- Duff, M. C., & Brown-Schmidt, S. (2012). The hippocampus and the flexible use and processing of language. *Frontiers in Human Neuroscience*, 6(April), 69. <http://dx.doi.org/10.3389/fnhum.2012.00069>.
- Duncan, K., Curtis, C., & Davachi, L. (2009). Distinct memory signatures in the hippocampus: Intentional States distinguish match and mismatch enhancement signals. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 29(1), 131–139. <http://dx.doi.org/10.1523/JNEUROSCI.2998-08.2009>.
- Eichenbaum, H., & Cohen, N. J. (2001). *From conditioning to conscious recollection: memory systems of the brain*. New York, NY: Oxford University Press.
- Federmeier, K. D., & Kutas, M. (2005). Aging in context: Age-related changes in context use during language comprehension. *Psychophysiology*, 42(2), 133–141. <http://dx.doi.org/10.1111/j.1469-8986.2005.00274.x>.
- Federmeier, K. D., McLennan, D. B., De Ochoa, E., & Kutas, M. (2002). The impact of semantic memory organization on sentence context information on spoken language processing by younger and older adults: An ERP study. *Psychophysiology*, 39(2), 133–146. <http://dx.doi.org/10.1017/S0048577202001373>.
- Federmeier, K. D., van Petten, C., Schwartz, T. J., & Kutas, M. (2003). Sounds, words, sentences: Age-related changes across levels of language processing. *Psychology and Aging*, 18(4), 858–872. <http://dx.doi.org/10.1037/0882-7974.18.4.858>.
- Ferreira, V. S., Bock, K., Wilson, M. P., & Cohen, N. J. (2008). Memory for syntax despite memory amnesia. *Psychological Science*, 19(9), 940–946.
- Fine, A. B., & Florian Jaeger, T. (2013). Evidence for implicit learning in syntactic comprehension. *Cognitive Science*, 37(3), 578–591. <http://dx.doi.org/10.1111/cogs.12022>.
- Fine, A. B., Jaeger, T. F., Farmer, T. A., & Qian, T. (2013). Rapid expectation adaptation during syntactic comprehension. *PLoS ONE*, 8(10), <http://dx.doi.org/10.1371/journal.pone.0077661>.
- Fjell, A. M., Westlye, L. T., Grydeland, H., Amlien, I., Espeseth, T., Reinvang, I., ... Walhovd, K. B. (2013). Critical ages in the life course of the adult brain: Nonlinear subcortical aging. *Neurobiology of Aging*, 34(10), 2239–2247. <http://dx.doi.org/10.1016/j.neurobiolaging.2013.04.006>.
- Garnsey, S. M., Pearlmutter, N. J., Myers, E., & Lotocky, M. A. (1997). The contributions of verb bias and plausibility to the comprehension of temporarily ambiguous sentences. *Journal of Memory and Language*, 37(1), 58–93. <http://dx.doi.org/10.1006/jmla.1997.2512>.
- Hallett, P. E. (1986). Eye movements. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (Vol. 1, pp. 10.1–10.112). New York, NY: Wiley.
- Hannula, D. E., Tranel, D., & Cohen, N. J. (2006). The long and the short of it: Relational memory impairments in amnesia, even at short lags. *Journal of Neuroscience*, 26(32), 8352–8359. <http://dx.doi.org/10.1523/JNEUROSCI.5222-05.2006>.
- Harrison, L. M., Duggins, A., & Friston, K. J. (2006). Encoding uncertainty in the hippocampus. *Neural Networks*, 19(5), 535–546. <http://dx.doi.org/10.1016/j.neunet.2005.11.002>.
- Heyselaar, E., Segaert, K., Walvoort, S. J., Kessels, R. P., & Hagoort, P. (2017). The role of nondeclarative memory in the skill for language: Evidence from syntactic priming in patients with amnesia. *Neuropsychologia*, 101, 97–105.
- Jaeger, T. F., & Snider, N. E. (2013). Alignment as a consequence of expectation adaptation: Syntactic priming is affected by the prime’s prediction error given both prior and recent experience. *Cognition*, 127(1), 57–83. <http://dx.doi.org/10.1016/j.cognition.2012.10.013>.
- Kaschak, M. P., & Glenberg, A. M. (2004). This construction needs learned. *Journal of Experimental Psychology: General*, 133(3), 450–467. <http://dx.doi.org/10.1037/0096-3445.133.3.450>.
- Kim, G., Lewis-Peacock, J. A., Norman, K. A., & Turk-Browne, N. B. (2014). Pruning of memories by context-based prediction error. *Proceedings of the National Academy of Sciences*, 111(24), 8997–9002. <http://dx.doi.org/10.1073/pnas.1319438111>.
- Kleiner, M., Brainard, D., & Pelli, D. (2007). What’s new in Psychtoolbox-3? [EVCV Abstract Supplement]. Perception, 36.
- Klooster, N. B., & Duff, M. C. (2015). Remote semantic memory is impoverished in hippocampal amnesia. *Neuropsychologia*, 79, 42–52. <http://dx.doi.org/10.1016/j.neuropsychologia.2015.10.017>.
- Knowlton, B. J., Ramus, S. J., & Squire, L. R. (1992). Intact artificial grammar learning in amnesia. *Psychological Science*, 3(3), 172–179. <http://dx.doi.org/10.7897/2277-4343.04323>.
- Kumaran, D., & Maguire, E. A. (2007). Match-mismatch processes underlie human hippocampal responses to associative novelty. *The Journal of Neuroscience*, 27(32), 8517–8524. <http://dx.doi.org/10.1523/JNEUROSCI.1677-07.2007>.
- Kurczek, J., Brown-Schmidt, S., & Duff, M. C. (2013). Hippocampal contributions to language: Evidence of referential processing deficits in amnesia. *Journal of Experimental Psychology: General*, 142(4), 1346–1354. <http://dx.doi.org/10.1037/a0034026>.
- Kurczek, J., Wechsler, E., Ahuja, S., Jensen, U., Cohen, N., Tranel, D., & Duff, M. C. (2015). Differential contributions of hippocampus and medial prefrontal cortex to self-projection and self-referential processing. *Neuropsychologia*, 73, 116–126.
- Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2015). lmerTest: tests in linear mixed effects models, 2015. R package version, 2-0.
- Long, N. M., Lee, H., & Kuhl, B. A. (2016). Hippocampal mismatch signals are modulated by the strength of neural predictions and their similarity to outcomes. *The Journal of Neuroscience*, 36(50), 1850–1916. <http://dx.doi.org/10.1523/JNEUROSCI.1850-16.2016>.
- Luka, B. J., & Barsalou, L. W. (2005). Structural facilitation: Mere exposure effects for grammatical acceptability as evidence for syntactic priming in comprehension. *Journal of Memory and Language*, 52(3), 444–467. <http://dx.doi.org/10.1016/j.jml.2005.01.013>.
- MacDonald, M. C., Pearlmutter, N. J., & Seidenberg, M. S. (1994). The lexical nature of syntactic ambiguity resolution. *Psychological Review*, 101(4), 676–703. <http://dx.doi.org/10.1037/0033-295X.101.4.676>.
- MacKay, D. G., Stewart, R., & Burke, D. M. (1998). H.M. revisited: Relations between language comprehension, memory, and the hippocampal system. *Journal of Cognitive Neuroscience*, 10(3), 377–394. <http://dx.doi.org/10.1162/089892998562807>.
- McMurray, B., Samelson, V. M., Lee, S. H., & Bruce Tomblin, J. (2010). Individual differences in online spoken word recognition: Implications for SLI. *Cognitive Psychology*, 60(1), 1–39. <http://dx.doi.org/10.1016/j.cogpsych.2009.06.003>.
- Payne, B. R., Grison, S., Gao, X., Christianson, K., Morrow, D. G., & Stine-Morrow, E. A. L. (2014). Aging and individual differences in binding during sentence understanding: Evidence from temporary and global syntactic attachment ambiguities. *Cognition*, 130(2), 157–173. <http://dx.doi.org/10.1016/j.cognition.2013.10.005>.
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, 10, 437–442. <http://dx.doi.org/10.1163/156856897X00366>.
- Piai, V., Anderson, K. L., Lin, J. J., Dewar, C., Parvizi, J., Dronkers, N. F., & Knight, R. T. (2016). Direct brain recordings reveal hippocampal rhythm underpinnings of language processing. *Proceedings of the National Academy of Sciences*, 201603312. <http://dx.doi.org/10.1073/pnas.1603312113>.
- Ranganath, C., & Esposito, M. D. (2001). Medial temporal lobe activity associated with

- active maintenance of novel information. *Neuron*, 31, 865–873.
- Raz, N., Lindenberger, U., Rodrigue, K. M., Kennedy, K. M., Head, D., Williamson, A., ... Acker, J. D. (2005). Regional brain changes in aging healthy adults: General trends, individual differences and modifiers. *Cerebral Cortex*, 15(11), 1676–1689. <http://dx.doi.org/10.1093/cercor/bhi044>.
- Rodd, J. M., Cai, Z. G., Betts, H. N., Hanby, B., Hutchinson, C., & Adler, A. (2016). The impact of recent and long-term experience on access to word meanings: Evidence from large-scale internet-based experiments. *Journal of Memory and Language*, 87, 16–37. <http://dx.doi.org/10.1016/j.jml.2015.10.006>.
- Rubin, R. D., Brown-Schmidt, S., Duff, M. C., Tranel, D., & Cohen, N. J. (2011). How do I remember that I know you know that I know? *Psychological Science*, 22(12), 1574–1582. <http://dx.doi.org/10.1177/0956797611418245>.
- Ryan, J. D., Althoff, R. R., Whitlow, S., & Cohen, N. J. (2000). Amnesia is a deficit in relational memory. *Psychological Science*, 11(6), 454–461. <http://dx.doi.org/10.1111/1467-9280.00288>.
- Ryskin, R. A., Qi, Z., Duff, M. & Brown-Schmidt, S. (2017b). Syntactic variability between and within speakers: When to adapt, when to generalize? In Paper presented at the 30th Annual CUNY Conference on Human Sentence Processing, Cambridge, MA.
- Ryskin, R. A., Qi, Z., Duff, M. & Brown-Schmidt, S. (2018). The effects of aging on verb bias knowledge and learning. In Paper presented at the 31st Annual CUNY Conference on Human Sentence Processing, Davis, CA.
- Ryskin, R. A., Qi, Z., Duff, M. C., & Brown-Schmidt, S. (2017a). Verb biases are shaped through lifelong learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 43(5), 781–794.
- Schapiro, A. C., Gregory, E., Landau, B., McCloskey, M., & Turk-Browne, N. B. (2014). The Necessity of the medial temporal lobe for statistical learning. *Journal of Cognitive Neuroscience*, 26(8), 1736–1747. <http://dx.doi.org/10.1162/jocn.2012.06.056>.
- Schapiro, A. C., Kustner, L. V., & Turk-Browne, N. B. (2012). Shaping of object representations in the human medial temporal lobe based on temporal regularities. *Current Biology*, 22(17), 1622–1627. <http://dx.doi.org/10.1016/j.cub.2012.06.056>.
- Schapiro, A. C., Turk-Browne, N. B., Botvinick, M. M., & Norman, K. A. (2017). Complementary learning systems within the hippocampus: A neural network modeling approach to reconciling episodic memory with statistical learning. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372(1711), <http://dx.doi.org/10.1101/051870>.
- Schmolck, H., Stefanacci, L., & Squire, L. R. (2000). Detection and explanation of sentence ambiguity are unaffected by hippocampal lesions but are impaired by larger temporal lobe lesions. *Hippocampus*, 7(7), 759–770.
- Snedeker, J., & Trueswell, J. C. (2004). The developing constraints on parsing decisions: The role of lexical-biases and referential scenes in child and adult sentence processing. *Cognitive Psychology*, 49(3), 238–299. <http://dx.doi.org/10.1016/j.cogpsych.2004.03.001>.
- Spivey, M. J., & Tanenhaus, M. K. (1998). Syntactic ambiguity resolution in discourse: Modeling the effects of referential context and lexical frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 24(6), 1521–1543. <http://dx.doi.org/10.1037/0278-7393.24.6.1521>.
- Spivey-Knowlton, M. J., & Sedivy, J. C. (1995). Resolving attachment ambiguities with multiple constraints. *Cognition*, 55, 227–267. [http://dx.doi.org/10.1016/0010-0277\(94\)00647-4](http://dx.doi.org/10.1016/0010-0277(94)00647-4).
- Spivey-Knowlton, M. J., Trueswell, J. C., & Tanenhaus, M. K. (1993). Context effects in syntactic ambiguity resolution: Discourse and semantic influences in parsing reduced relative clauses. *Canadian Journal of Experimental Psychology*, 47(2), 276–309. <http://dx.doi.org/10.1037/h0078826>.
- Tanenhaus, M. K., Spivey-Knowlton, M. J., Eberhard, K. M., & Sedivy, J. C. (1995). Integration of visual and linguistic information in spoken language comprehension. *Science*, 268, 1632–1634.
- Taraban, R., & McClelland, J. L. (1988). Constituent attachment and thematic role assignment in sentence processing: Influences of content-based expectations. *Journal of Memory and Language*, 27, 597–632. [http://dx.doi.org/10.1016/0749-596X\(88\)90011-3](http://dx.doi.org/10.1016/0749-596X(88)90011-3).
- Tooley, K. M., Swaab, T. Y., Boudewyn, M. A., Zirnstein, M., & Traxler, M. J. (2014). Evidence for priming across intervening sentences during on-line sentence comprehension. *Language and Cognitive Processes*, 29(3), 289–311. <http://dx.doi.org/10.1080/01690965.2013.770892>.
- Tooley, K. M., Traxler, M. J., & Swaab, T. Y. (2009). Electrophysiological and behavioral evidence of syntactic priming in sentence comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 35(1), 19–45. <http://dx.doi.org/10.1037/a0013984>.
- Trude, A. M., Duff, M. C., & Brown-Schmidt, S. (2014). Talker-specific learning in amnesia: Insight into mechanisms of adaptive speech perception. *Cortex*, 54, 117–123.
- Trueswell, J. C. (1996). The role of lexical frequency in syntactic ambiguity resolution. *Journal of Memory and Language*, 35(3), 566–585. <http://dx.doi.org/10.1006/jmla.1996.0030>.
- Trueswell, J. C., Tanenhaus, M. K., & Kello, C. (1993). Verb-specific constraints in sentence processing: Separating effects of lexical preference from garden-paths. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 19(3), 528–553. <http://dx.doi.org/10.1037//0278-7393.19.3.528>.
- Turk-Browne, N. B., Scholl, B. J., Chun, M. M., & Johnson, M. K. (2009). Neural evidence of statistical learning: Efficient detection of visual regularities without awareness. *Journal of Cognitive Neuroscience*, 21(10), 1934–1945. <http://dx.doi.org/10.1162/jocn.2009.21131>.
- Walhovd, K. B., Westlye, L. T., Amlie, I., Espeseth, T., Reinvang, I., Raz, N., ... Fjell, A. M. (2011). Consistent neuroanatomical age-related volume differences across multiple samples. *Neurobiology of Aging*, 32(5), 916–932. <http://dx.doi.org/10.1016/j.neurobiolaging.2009.05.013>.
- Warren, D., & Duff, M. C. (2014). Not so fast: Hippocampal amnesia slows word learning despite successful fast mapping. *Hippocampus*, 24(8), 920–933.
- Wells, J. B., Christiansen, M. H., Race, D. S., & MacDonald, M. C. (2009). Experience and sentence processing: Statistical learning and relative clause comprehension. *Cognitive Psychology*, 58(2), 250–271. <http://dx.doi.org/10.1016/j.cogpsych.2008.08.002>.
- Wilson, M. P., & Garnsey, S. M. (2009). Making simple sentences hard: Verb bias effects in simple direct object sentences. *Journal of Memory and Language*, 60(3), 368–392. <http://dx.doi.org/10.1016/j.jml.2008.09.005>.