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Knowledge and learning of verb biases in amnesia

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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

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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