Methods

Participants

Ten participants (8 female, mean age 23.8), eight right-handed (as determined by the Edinburgh handedness inventory, Oldfield, 1971) were recruited from MIT and the surrounding Cambridge/Boston area and paid for their participation. The two left-handed individuals showed typical left lateralization for language. All were native speakers of English, had normal hearing and vision, and no history of language impairment. All participants gave informed consent in accordance with the requirements of the MIT's Committee on the Use of Humans as Experimental Subjects (COUHES).

Design, stimuli and procedure

Language localizer task

*** standard langloc, everyone saw two runs [NB: not relevant to the analyses described below]

Critical phrase-picture matching task

In the critical task, participants were presented with a phrase and then, some time later, an image that either did or did not correspond in meaning to the phrase. They were asked to decide whether the image matches the phrase in meaning.

Linguistic materials.
We selected 4 base noun phrases such as "a happy man in front of an old woman" (Table 1) from the 30 base phrases used in Gershman & Tenenbaum (2015). These phrases were all of the form: Determiner Adjective Noun Preposition Determiner Adjective Noun, where the first (head) noun phrase was modified by the second noun phrase. The prepositions always referred to spatial relations. We had to restrict the number of base phrases to 4 because of the timing constraints of an fMRI session (see below). These particular phrases were chosen to maximize the ease of visual representation, and to diversify the relevant nouns in terms of their animacy (human-human for 1 base phrase, animal-animal for 1 base phrase, and object-object for 2 base phrases). Four additional versions of each base phrase were created following the design used in Gershman & Tenenbaum (2015). In particular, in the noun-change version the two nouns were swapped (e.g., a happy man in front of an old woman → a happy **woman** in front of an old **man**; swapped elements are marked in bold). Similarly, in the adjective-change version, the two adjectives were swapped (e.g., a happy man in front of an old woman → an **old** man in front of a **happy** woman), and in the preposition-change version, the preposition was changed to one that indicated the opposite spatial relation (e.g., a happy man in front of an old woman → a happy man **behind** an old woman). Finally, in the meaning-preservation version, the two noun phrases were swapped and the preposition was changed to the one with the opposite meaning, which lead to a phrase that preserved the meaning of the original phrase (a happy man in front of an old woman → an old woman behind a happy man). Thus, we had 4 items, with 5 versions (conditions) each (base, noun-change, adjective-change, preposition-change, and meaning-preservation), for a total of 20 phrases (see Table 1 for a complete list of materials).

Pictorial materials.
The pictorial materials were created in two steps. First, for each potential "character" (i.e., happy man, old woman, happy woman, old man, etc., for a total of 16 characters, 4 from each base phrase), 5 clipart images were selected from the Google Image Database (for the animal and object characters) or were created using BitStrips (www.bitstrips.com) (for the human characters). The human characters varied in race, posture, and clothing, and care was taken to ensure that each descriptor was clear (i.e., that the "happy" characters did not look old and that the "old" characters did not look happy). And second, these 80 images of individual characters (16 characters x 5 images per character) were used to create 25 composite images for each of 20 phrases, for a total of 500 images (see Figure 1 for sample images; all the 80 individual character images and the 500 composite images are available from the authors).

Procedure. Each trial (Figure 2) started with a 2s presentation of four images of individual characters: two characters that corresponded in meaning to the noun phrases used in the target phrase and two distractor characters where the objects remained the same, but the properties were switched. For example, for a phrase "a full glass in front of an empty bottle", participants would see a) a full glass, b) an empty bottle, c) an empty glass, and d) a full bottle. This was done to familiarize the participants with the characters to be used in the upcoming image. The critical phrase was then presented for 2s, followed by a fixation screen presented for between 5s and 9s (varied in increments of 1s). The critical image was then presented briefly, for 0.5s, and participants had to press one of two buttons to decide whether the image matched the phrase in meaning. They had 1.5s to respond (the duration of the image + 1s of additional fixation), after which they received feedback (a green checkmark or a red cross if they answered correctly or incorrectly, respectively). The response window was short in order to encourage participants to actively process the phrase for meaning rather than holding the phrase in phonological memory until the image is shown and then attempting to access its meaning and to compare it to the meaning depicted in the image.

Each participant saw each of 20 target phrases 6-10 times, for a total of 120-200 trials (24-40 for each of 5 conditions: base, noun-change, adjective-change, preposition-change, and meaning-preservation). Each phrase was paired with a matching image half of the time. Any particular image of a "character" was not used more than once in a target image within a run (so, for example, a different image of an empty bottle would be used for the target phrase "a full glass in front of an empty bottle" and "a full glass behind an empty bottle"). The trials were grouped into runs so that each run contained one instance of each of 20 phrases. Trials were separated by 1.5 s of fixation for a total run duration of 310s (5 min 10s). Each participant performed 6-10 runs.

fMRI data acquisition, processing, and modeling

Data acquisition
***fill in later

Data preprocessing and modeling
*** fill in later

For both the language localizer and the critical phrase-picture matching task, effects were estimated using a General Linear Model (GLM) in which each experimental condition (sentences and nonwords for the language localizer, and each of twenty phrases for the critical task) was modeled with a boxcar function and convolved with the canonical hemodynamic response function (HRF). For the language localizer task, the boxcar corresponded to entire blocks, and for the critical task, the boxcar corresponded to the 2s of sentence presentation and the first 5 seconds of the inter-stimulus interval (ISI varied from 5 to 9 s but any extra ISI was modeled as a separate condition). Time derivatives of these condition regressors were included in the GLM in order to account for possible shifts in hemodynamic latency.

fMRI data analysis

For the critical analysis, we examined the similarity of the activation patterns between the base phrase condition and each of the "transformation" conditions (i.e., noun-change, adjective-change, preposition-change, and meaning-preservation). This analysis was restricted to the language network. In particular, we used a set of "parcels" derived from a group-level representation of neural activity for a language "localizer" task (Fedorenko et al., 2010) in 220 participants. These parcels correspond to the gross locations of language activations in individual participants, but here we just used the whole parcels without masking them with individual language localizer activation maps. In each participant, for each of four items we divided the data in half (odd-numbered runs and even-numbered runs) and computed a correlation in each of the 6 language parcels i) within each condition (e.g., happy man / old woman item base phrase odd runs vs. base phrase even runs), and critically, ii) between the base phrase condition and each of the "transformation" conditions (e.g., happy man / old woman item base phrase odd runs vs. noun-change even runs, and base phrase even runs vs. noun-change odd runs. These correlation values were averaged across the six parcels, and then between the odd/even and even/odd splits, to derive a set of four critical between-condition correlation values per participant per item: base to noun-change, base to adjective-change, base to preposition-change, and base to meaning-preservation. Finally, these values were averaged across the four items within each participant, and then across participants (Figure 4).

Results

Behavioural. Average accuracy across participants and conditions was 76.3% (st dev = 11.6%; range: 56.5% to 90.5%). Accuracies broken down by condition are shown in Figure 3.

fMRI. As shown in Figure 4, the pattern of between-condition spatial correlations appears to match the patterns of behavioral meaning similarity ratings reported in Gershman & Tenenbaum (2015), with the base phrase – meaning-preservation correlation being the highest, followed by the base phrase – adjective-change and base phrase – preposition-change correlations, with the base phrase – noun-change correlation being the lowest.

Brianna Pritchett 5/31/2017 11:33 AM

Comment [1]: This was mostly due to one bad run that this subject had where she only got 5% accuracy – I talked to her afterward and she just wasn't pressing the buttons hard enough. Without that run she goes up to 62% accuracy

Tables

Condition name	MAN item	CAT item	PEN item	GLASS item
Base phrase	A happy man in front of an old woman.	A black cat in front of a white dog.	A blue pen on a red folder.	A full glass in front of an empty bottle.
Noun change	A happy woman in front of an old man.	A black dog in front of a white cat.	A blue folder on a red pen.	A full bottle in front of an empty glass.
Adjective change	An old man in front of a happy woman.	A white cat in front of a black dog.	A red pen on a blue folder.	An empty glass in front of a full bottle.
Preposition change	A happy man behind an old woman.	A black cat behind a white dog.	A blue pen under a red folder.	A full glass behind an empty bottle
Meaning preservation	An old woman behind a happy man.	A white dog behind a black cat.	A red folder under a blue pen.	An empty bottle behind a full glass.

Table 1: Full set of sentence stimuli

Figures

	Base	NChange	AJChange	Prepchange	Meaningpres
man					
cat					
glass					
pen					

Figure 1: Sample stimuli for each of 20 phrases.

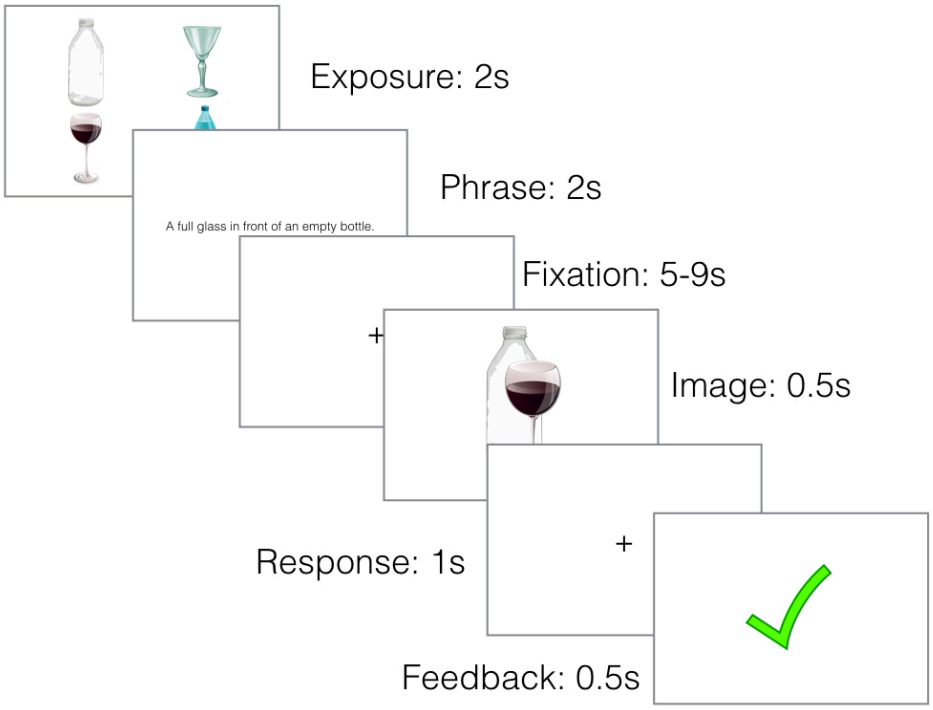

Figure 2: Sample trial

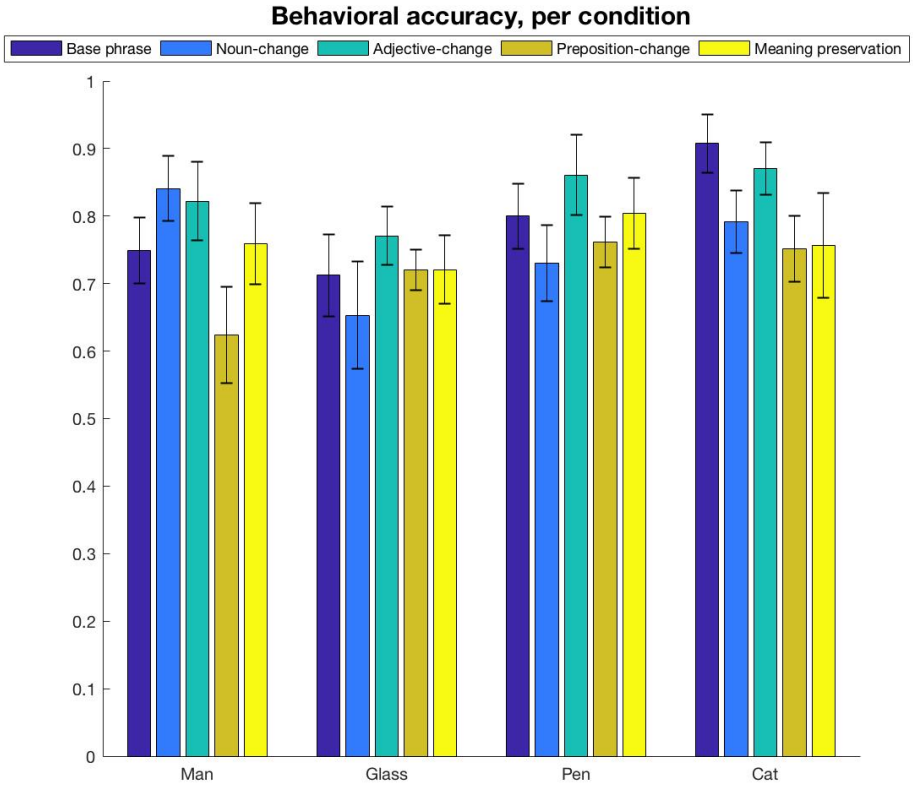

Figure 3: Behavioral data, broken down by condition.

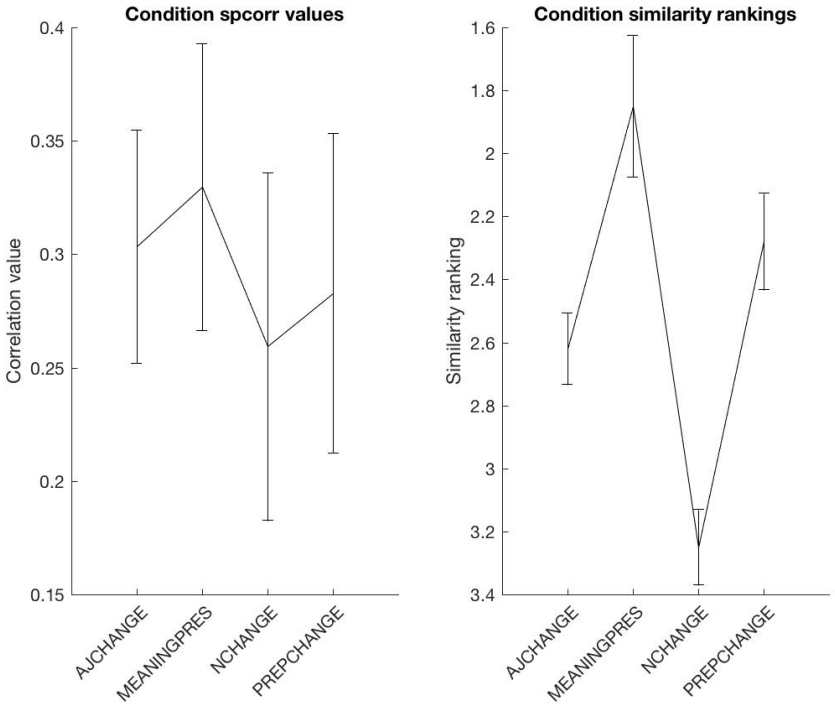

Figure 4: Spatial correlation results, compared to behavioural similarity ratings from Gershman & Tenenbaum (2015).