

# Supporting Information

Stephens et al. 10.1073/pnas.1008662107

## SI Methods

**Recording System.** We recorded the speaker's speech during the fMRI scan using a customized MR-compatible recording system (FOMRI II; Optoacoustics Ltd.). The MR recording system uses two orthogonally oriented optical microphones. The typical 3D spherical polarity of the dual-channel sensor is shown in Fig. S1. The reference microphone captures the background noise, and the source microphone captures both background noise and the speaker's speech utterances (signal). A dual-adaptive filter subtracts the reference input from the source channel (using least mean square approach). To achieve an optimal subtraction, the reference signal is adaptively filtered where the filter gains are learned continuously from the residual signal and the reference input. To prevent divergence of the filter when speech is present, a voice activity detector (VAD) is integrated into the algorithm. An additional speech-enhancement spectral-filtering algorithm further preprocesses the speech output to achieve a real-time speech enhancement.

**MRI Acquisition.** Subjects were scanned in a 3T head-only MRI scanner (Allegra; Siemens). A custom radiofrequency coil was used for the structural scans (NM-011 transmit head coil; Nova Medical). For fMRI scans, a time series of volumes was acquired using a T2\*-weighted EPI pulse sequence [repetition time (TR) = 1,500 ms; echo time (TE) = 30 ms; flip angle = 80°]. The volume included 25 slices of 3-mm thickness with 1-mm interslice gap (in-plane resolution = 3 × 3 mm<sup>2</sup>). T1-weighted high-resolution (1 × 1 × 1 mm) anatomical images were acquired for each observer with an MPRAGE pulse sequence to allow accurate cortical segmentation and 3D surface reconstruction. To minimize head movement, subjects' heads were stabilized with foam padding. Stimuli were presented using Psychophysics Toolbox in Matlab. High-fidelity MRI-compatible headphones (MR Confon) were fitted to provide considerable attenuation to the scanner noise and to present the audio stimuli to the subjects.

**Data Preprocessing.** fMRI data were preprocessed with the BrainVoyager software package (Brain Innovation, version 1.8) and with additional software written with Matlab. Preprocessing of functional scans included linear trend removal and high-pass filtering (up to six cycles per experiment). To correct for head motion, we used a 3D algorithm that adjusts for small head movements by rigid body transformations of all slices to the first reference volume. Detected head motions were less than 1 mm in size, which is well within the range of typical movements observed in other imaging studies. All functional images were transformed into a shared Talairach coordinate system so that corresponding brain regions are roughly spatially aligned. To further overcome misregistration across subjects, the data were spatially smoothed with a Gaussian filter of 6-mm full width at half-maximum value. To remove transient nonspecific signal elevation effects at the beginning of the experiment, and some preprocessing artifacts at the edges of the time courses, we excluded the first 15 and the last three timepoints of the experiments.

**Autocorrelations.** In principle, the correlations between shifted voxel time courses can complicate the interpretation of the  $\beta$  weights. In practice, these correlations are small, as shown by the mean voxel autocorrelation function, averaged across all brain locations in the speaker (Fig. S1). The autocorrelations are strongest for neighboring timepoints, but are small overall and decay rapidly. In addition, we decorrelated the model speaker

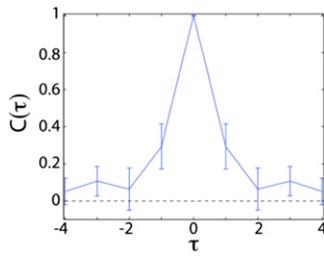
regressors and repeated the coupling categorization analysis reported below with no substantial changes. The weights  $\beta_i$  are thus an approximate independent measure of the contribution of the speaker dynamics for each shift. The stability of the model was assessed by calculating the condition number  $c = \lambda_1/\lambda_2$  of the covariance matrix, where  $\lambda_1$  and  $\lambda_2$  are the largest and smallest eigenvalues, respectively. Across the entire brain volume we find  $c_{\max} = 60$ , which is well below machine precision limits.

**Behavioral Assessment.** Immediately following the scan, the participants were asked to record the story they heard in as much detail as possible. Six independent raters scored each of these listener records according to a 115-point true/false questionnaire (SI Methods), and the resulting score was used as a quantitative and objective measure of the listener's understanding. Among the raters, there was little variance in the scores assigned to each listener (Fig. S4), and thus the variance in behavioral scores among listeners accurately reflects the variability of their natural experience. To connect behavioral scores to neural activity, we analyzed the couplings derived from the ( $n = 11$ ) pairings between the speaker and the individual listeners. For each listener, we defined the spatial extent of the speaker-listener coupling in two distinct ways: (i) the number of significant couplings identified through Eq. 1, and (ii) the number of significantly advanced couplings (a subset of  $i$  with advanced contrast  $P$  value,  $P < 0.03$ ). In each case, we then ranked both the listener's behavioral scores and the extent of significant speaker-listener coupling and computed the correlation between ranks.

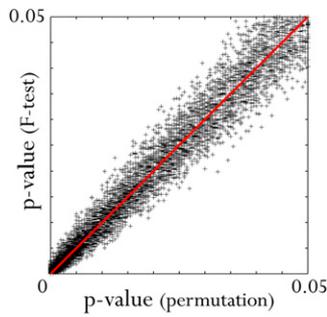
**A Transcript of the Story.** I am going to tell you a story about my prom experience. I know everybody has some crazy prom stories, but, well, just wait. I was a freshman in high school in Miami, Florida, and I'm new to the freshman scene. I'm new to the high school scene, I should say, and it's almost December so I've been in high school for about 3 months, and this boy Charles asks me out. He's British, he's a junior, and he's really cute but sort of shy but just, well, it doesn't matter. So I say yes, I'm excited. He comes and picks me up in this really old, beat-up white Toyota, and he has two tapes in his car: Queen and Oasis. And so I ask him if he only listens to English bands when I get in the car and he gets a little offended. So I knew that, um, it just wasn't gonna work out with us. But so we go out and it's sort of awkward and whatever, and nothing really happens. And then we actually go out again and it's also awkward. And then the next day at school, this is like two weeks later, we're sort of with other people talking about prom, which is now months and months away. And I leave to go to class, but he comes with me and we're still sort of talking about prom, in like a general sense about what prom is more than, you know, specifics about this prom. But for some reason, out of the blue, he asks me to go to his prom with him. And, I mean, I'm a freshman girl, and it's really exciting, I never would have thought of going to the prom as a freshman, so of course I say yes, not really thinking about it. I think it's pretty weird but I just go with it. Um, and that's sort of that. And then that weekend I was at a party on the beach at this big house that was like the party house of my high school, at least freshman and sophomore year because his house was right on the beach and so the police were not roaming around those beaches. Um, anyway, so I'm at this party and I'm getting a beer out of the keg and I had never really done that much so of course I'm horrible at it and it's like 85% foam, and I notice that the guy behind me is this guy Amir. He's this really good-looking senior and well, my high school was a really big swimming high school. A lot of people went there

for swimming from all over the world, and so it was half a boarding school also, so there was a boys' dorm and a girls' dorm. Amir was a swimmer and he lived in the boys' dorm. And he was sort of a popular senior guy. And so he takes over and pours me this beer, of course perfectly foamless. And as he's passing it back to me, the guy behind me gets pushed or something, and pushes into me, and of course I spill the beer all over Amir, and that's how we meet. And it's sort of this high school romance fantasy, where we were just totally smitten. And so we start going out, and it's really fun. I don't have my license at this point, I have a permit, and so he teaches me how to drive. He lives in the boys' dorm and so his friends and him put me in a box, a cardboard box, and wrapped it up, and actually carried me, snuck me into the dorm as like a package. It was very funny, it was all fun, I was very happy. And then so we've been together for over two months or so and it comes time for people to kind of start talking about prom. So at this point I've basically forgotten that Charles was even there and just assumed that we both realized that it wasn't really working out and went our separate ways. And he knew that I was now with Amir and I just assumed it was fine. But so I'm at school and I'm sitting in the quad and Charles comes over to me and he sits down and says 'I just wanted to you know discuss with you our plans for prom'. And I'm like 'um, I, um . . .' I just didn't know what to say. So, I feel really badly about it, he obviously was, uh, hurt, and not going to let it go. And I felt badly, so I decide that I'm going to go to the prom with Charles and just meet up with Amir after. So then the day of the prom comes around, and on top of all of this sort of drama with this boy situation, my family—we're a big sailing family. We like to sail to see places, or maybe vice versa. So we take a lot of trips on sailboats, just the family sailing, like around Greece or France or wherever. And that particular summer we had planned a trip to go sailing in the British Virgin Islands, which is really known for its scuba diving. So we all decide to get certified for scuba diving. And of course the only weekend we could do it—it's like a two-weekend consecutive course—the only weekends we can do it are the weekend before the prom and the weekend of the prom. So the first weekend is all sort of in the pool, and the second weekend you actually go out into the ocean and do a real dive off of Miami Beach. And we left at like 8 in the morning, we're supposed to get back at three. So I think ok, this is fine, I'll get back home by like 4 and I'll have like two hours to get ready for this prom. Which is a really big deal, especially as a freshman girl, I was really nervous about prom in general. So we go scuba diving, and that's a whole nother story, my family is just really crazy on this boat. My mother is terrified, literally terrified, but just trying to stay calm, and when she's under any sort of pressure she sort of reverts back to this very thick New York accent, so she's just freaking out about her tank or whatever in this thick New York accent. And my father, who's sort of big tall and prominent, tough, manly man, and he's completely seasick, just trying not to throw up the whole time. Um, but, it was just really this crazy experience. So anyway, we're getting back, we've scuba dived, we've gone through the whole thing, and of course the boat breaks down. So we have to wait for like a tugboat to come bring us to shore, and we finally get back, and we're pulling into my house at like 6 o'clock, like two and a half hours late, just as Charles, who's always on time, of course, is pulling up. We pull up together. And, I don't know if you've ever been scuba diving, but pretty much the worst you'll ever look is after you go scuba diving.

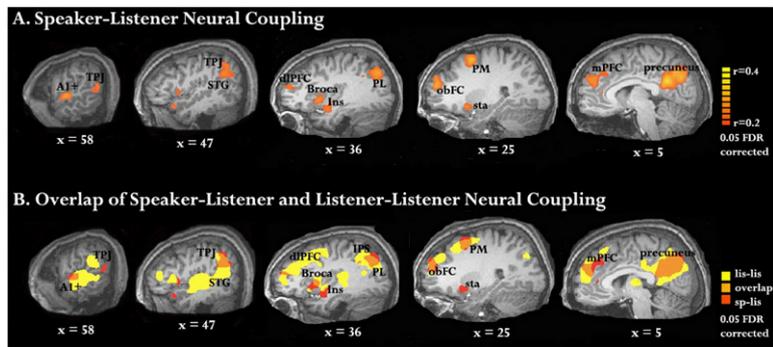
You've been under 60 feet of water, which is two atmospheres of pressure, for an hour and a half. You have a goggle mark permanently sketched into your face, which takes like 5 hours to get rid of that. And um, just your hair, it's just a mess, you're just a mess. And now I have approximately 5 minutes to get ready for the prom. So I'm like trying to put on make-up while my sister is shaving my legs, while my mom is brushing my hair. And I sort of put it all together as quickly as possible, throw on a dress, and leave. So now I'm on my way to the prom with Charles and it's very awkward, very awkward. We go to this dinner thing at one of his friends and it's just sort of an awkward situation in general. But we finally get to the prom and I'm looking around for Amir, and I can't find him anywhere. So I go to the bathroom, and I come back and I hear shouting in the back corner. And Amir is just totally drunk and is starting a fight with Charles. He's like about to hit him. And I run over and I grab Amir and we leave. And it's fine and we decide to go to the after party pretty much immediately. So we're walking to the car, and Amir had drove but he obviously couldn't drive 'cause he was drunk, so I drive. And Amir is going through his pockets to find his keys to give me the keys and he trips in the parking lot over one of those parking space indicator things, and his hands are in his pockets and he's not fast enough when he's drunk to pull his hands out so he just falls flat on his face. And he looks up and there's blood running out of his nose and all over and he's just a bloody mess. So I run back to the bathroom and I get paper towels and whatnot and I clean him up a bit. And we get in the car and just start driving and I'm thinking this has been the most absurd day, but of course I thought that way too soon because we're driving and Amir is like playing air guitar or something in the passenger seat and I'm just trying to get us there and get out of the car. And so I'm driving on US1, and there's two lanes going one way and two lanes going the other, and every once in a while there's a turning lane. And there was a car accident in one of these turning lanes. And I'm driving slowly, there's lights and traffic and stuff so I'm not going quickly at all. And there was this fender bender and Amir, I'm not exactly sure what he does, but he sort of grabs my arm and I sort of turn, and I end up crashing into this accident that's already there. And so, um, so by already there I mean like nobody's hurt, it was a very light light hit, no cars were ruined or anything, but the police are already there, and all of the people are already there, like they're all watching it happen. So the policeman comes over, and I don't have my license, by the way. I have a permit so I can be driving with Amir cause he's 18, but he's wasted, I mean, he's still playing air guitar when the policeman comes over and his face is bloody. And so I give him my permit and the registration and he's like uh I need his license, so I give him Amir's license as well. And I'm thinking I'm done for. I'm thinking I'm going to jail for diving without a license with this drunk dude and I'm thinking it's all over for me. So the policeman leaves and I'm really freaking out. And he comes back like 20 minutes later, and, I'm not lying, he hands me back my license and he says to me, 'I'm sorry Miss Silbert, but somehow your registration has blown away and I cannot find it'. And he was so embarrassed about losing my registration that he tells me to drive on my way. For real. So I drive away as quickly as I can and I finally get to the after party house and I get out of the car and Amir passes out on the beach and I call my mom and have her pick me up. And that's it.



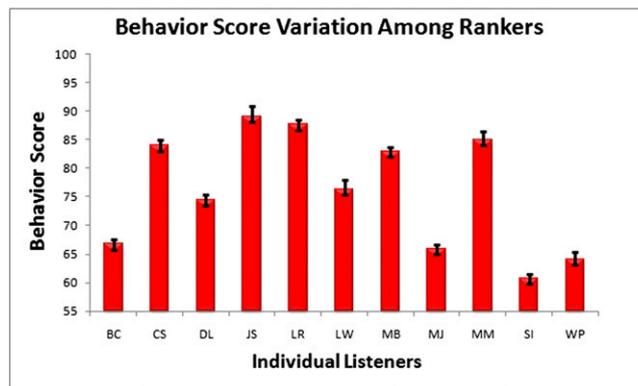
**Fig. S1.** Decay of temporal correlations. We show the voxel autocorrelation function averaged across all brain regions. Error bars denote SDs. Temporal correlations are strongest for neighboring timepoints ( $\pm 1$ ) but are small overall and decay rapidly in time.



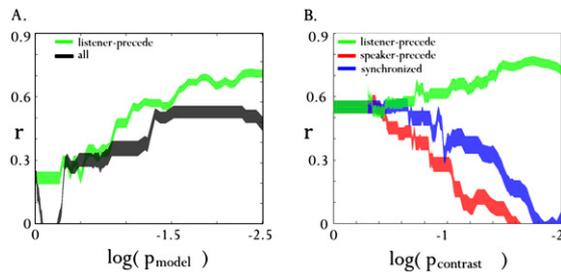
**Fig. S2.** The equivalence between  $F$  test (parametric) and shuffled (nonparametric) hypothesis testing in our study. We plot model  $P$  values obtained by an  $F$  test against  $P$  values obtained although a null model constructed by random permutation ( $n = 1,000$ ) of the time series.



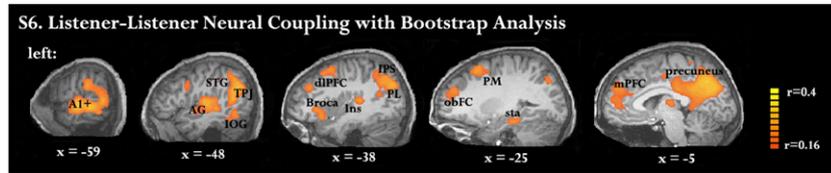
**Fig. S3.** The speaker–listener neural coupling within the right hemisphere. Figure layout is identical to that in Fig. 2A.



**Fig. S4.** The quantitative measure of story comprehension varies little among the different rankers who score the written answers. Error bars on the average score for each listener reflect the SD among the rankers.



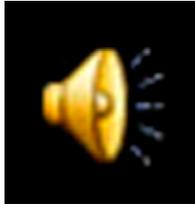
**Fig. S5.** The rank correlation between the extent of neural coupling and story comprehension grows with both temporal asymmetry (smaller contrast  $P$  values) and overall significance threshold (smaller model  $P$  values). (A) Plot of the activation/understanding rank correlation as a function of the model  $P$  values (black) and listener precedes (green) couplings (contrast  $P$  value fixed to  $P < 0.03$ ). (B) Plot of the activation/understanding rank correlation as a function of the temporal asymmetry (contrast  $P$  value) for speaker precedes (red), synchronous (blue), and listener precedes (green) couplings (model  $P$  value fixed to FDR,  $\gamma = 0.05$ ).



**Fig. S6.** Significant listener-listener couplings identified using shuffled bootstrap estimates of the null distribution, resulting in more extensive listener-listener alignment. Figure layout is identical to that in Fig. 2A.

**Table S1. Talairach coordinates of ROIs**

Anatomical region	Hemisphere	Talairach coordinates		
		X	Y	Z
A1+	Right	57	-9	6
	Left	-57	-20	5
Parietal lobule	Right	42	-46	31
	Right	56	-49	17
TPJ	Left	-47	-55	21
	Right	42	11	7
Broca	Left	-34	19	-10
	Right	35	8	3
Insula	Left	-32	13	-4
Anterior STG	Right	44	15	-15
Orbitofrontal cortex	Right	25	52	22
	Right	24	8	52
Premotor cortex	Left	-13	-4	69
	Right	6	-59	29
Precuneus	Left	-6	-65	26
	Right	6	42	27
mPFC	Left	-8	42	13
Insula	Left	-39	-77	25
mPFC	Left	-40	29	21
Inferior occipital gyrus	Left	-50	-57	-5



**Movie S1.** A segment of the audio recording of the story told by the speaker in the fMRI scanner and then played for 11 listeners.

[Movie S1](#)