Spared bottom-up but impaired top-down interactive effects during naturalistic language processing in schizophrenia

Citation for published version:
Rabagliati, H, Delaney-Busch, N, Snedeker, J & Kuperberg, GR 2019, 'Spared bottom-up but impaired top-down interactive effects during naturalistic language processing in schizophrenia: Evidence from the visual world paradigm' Psychological Medicine , vol. 49, no. 8, pp. 1335-1345. DOI: 10.1017/S0033291718001952

Digital Object Identifier (DOI):
10.1017/S0033291718001952

Published In:
Psychological Medicine

Spared bottom-up but impaired top-down interactive effects during naturalistic language processing in schizophrenia: Evidence from the visual world paradigm

Hugh Rabagliati[1,2,3], Nathaniel Delaney-Busch[1], Jesse Snedeker[2] and Gina Kuperberg[1,4]

[1] Department of Psychology, Tufts University, Medford, MA 02155, U.S.A.
[2] Department of Psychology, Harvard University
[3] School of Philosophy, Psychology and Language Sciences, University of Edinburgh
[4] Department of Psychiatry and the Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Harvard Medical School, Charlestown, MA 02129, U.S.A.

Please address correspondence to:
Hugh Rabagliati
School of Philosophy, Psychology and Language Sciences
University of Edinburgh
Edinburgh, UK
EH8 9JZ
hugh.rabagliati@ed.ac.uk

Word count (abstract): 250.
Word Count (total) 5531
Figures: 2
Tables: 3

Abstract

Background

People with schizophrenia process language in unusual ways, but the causes of these abnormalities are unclear. In particular, it has proven difficult to empirically disentangle explanations based on impairments in the top-down processing of higher-level information from those based on the bottom-up processing of lower-level information.

Methods

To distinguish these accounts, we used visual world eye-tracking, a paradigm that measures spoken language processing during real-world interactions. Participants listened to and then acted out syntactically ambiguous spoken instructions (e.g., "*tickle the frog with the feather",* which could either specify how to tickle a frog, or which frog to tickle). We contrasted how 24 people with schizophrenia and 24 demographically-matched controls used two types of lower-level information (prosody and lexical representations) and two types of higher-level information (pragmatic and discourse-level representations) to resolve the ambiguous meanings of these instructions. Eye-tracking allowed us to assess how participants arrived at their interpretation in real time, while recordings of participants' actions measured how they ultimately interpreted the instructions.

Results

We found a striking dissociation in participants' eye movements: the two groups were similarly adept at using lower-level information to immediately constrain their interpretations of the instructions, but only controls showed evidence of fast top-down use of higher-level information. People with schizophrenia, nonetheless, did eventually reach the same interpretations as controls.

Conclusions

These data suggest that language abnormalities in schizophrenia partially result from a failure to use higher-level information in a top-down fashion, to constrain the interpretation of language as it unfolds in real time.

Key words: Schizophrenia; Language; Eye movements; Prediction; Visual World Paradigm

Spared bottom-up but impaired top-down interactive effects on naturalistic spoken language comprehension in schizophrenia.

Language is the backbone of interpersonal interaction and an essential part of human cognition: To understand or speak a sentence requires the coordination of a range of processes, ranging from low-level perception to high-level social cognition. In schizophrenia, language dysfunction has long been noted (Andreasen, 1979a, 1979b; Bleuler, 1911/1950; Kuperberg, 2010a), and is most obviously seen in the disorganized ('thought-disordered') speech produced by some patients (Andreasen, 1986; Bleuler, 1911/1950). But abnormalities in language comprehension can also be detected in the absence of overt thought disorder (for reviews see Brown & Kuperberg, 2015; Kuperberg, 2010b) and these can predict psychosocial function (e.g., Bowie & Harvey, 2008; Holshausen, Harvey, Elvevåg, Foltz, & Bowie, 2014; Swaab et al., 2013). Understanding the basis of abnormal language processing in schizophrenia therefore has important general implications for understanding the disorder's cognitive architecture more broadly, particularly the relationships between perceptual and higher-order disturbances that characterize the disorder (Brown & Kuperberg, 2015). Moreover, the important role that language plays in social interaction suggest that understanding these linguistic abnormalities may shed light on the everyday social challenges faced by people with schizophrenia.

Abnormalities of language in schizophrenia have been described at multiple levels, including sentence and discourse processing (Boudewyn, Carter, & Swaab, 2012; Cohen & Servan-Schreiber, 1992; Ditman & Kuperberg, 2007; Kuperberg, McGuire, & David, 1998), pragmatic inferencing (Bambini et al., 2016; Frith, 2004), lexico-semantic associations (Elvevåg, Foltz, Weinberger, & Goldberg, 2007; Kreher, Goff, & Kuperberg, 2009; Mathalon, Faustman, & Ford, 2002; Minzenberg, Ober, & Vinogradov, 2002; Spitzer, Braun, Hermle, & Maier, 1993; Titone & Levy, 2004), phonology and orthography (Revheim et al., 2014; Whitford et al., 2013; Whitford, O'Driscoll, & Titone, 2017), and prosody (Kantrowitz, Hoptman, Leitman, Silipo, & Javitt, 2014). While higher- and lower-level language abnormalities in schizophrenia have usually been discussed independently, some have proposed that they are linked, with two major theories discussing the nature of these links.

The first 'bottom-up' theory proposes that lower-level impairments cascade up to cause higher-level language abnormalities in schizophrenia. This proposal assumes that the primary locus of linguistic dysfunction is in the perception and propagation of lower-level information (such as speech sounds or early visual representations) up the linguistic hierarchy, driving abnormalities at higher levels of representation, such as the interpretation of a sentence's meaning (Jahshan, Wynn, & Green, 2013; Javitt, 2009; Javitt & Freedman, 2015; Kantrowitz et al., 2014; Leitman et al., 2005; Revheim et al., 2014).

The second 'top-down interactive' theory proposes that linguistic abnormalities in schizophrenia stem from disruptions of the fast interactions *between* higher- and lower-level representations as language is comprehended. This theory (see Brown & Kuperberg, 2015 for a recent review) is based on models of typical language processing that posit constant communication between higher and lower-level representations during language comprehension (Elman, Hare, & McRae, 2004; McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995), an idea that is echoed in more general cognitive models of schizophrenia (e.g. Cohen & Servan-Schreiber, 1992). For example, probabilistic predictive frameworks propose a crucial role of top-down inputs from higher-level representations in *constraining* activity at lower-level representations (Brown & Kuperberg, 2015; Kuperberg & Jaeger, 2016). If these predictive interactions are disrupted in schizophrenia, this would result in unconstrained bottom-up activity (Corlett, Frith, & Fletcher, 2009; Fletcher & Frith, 2009), and thus abnormal patterns of language processing (Brown & Kuperberg, 2015).

Although these two theories appear distinct, they have proven difficult to disentangle (see Brown & Kuperberg, 2015). For example, some researchers have taken correlations between lower- and higher-level language abnormalities in schizophrenia as evidence for the first theory (Jahshan et al., 2013; Kantrowitz et al., 2014; Leitman et al., 2005), but these data are equally well explained by the second. Conversely, others have taken impairments in patients' use of higher-level discourse representations, but preserved sensitivity to simple lexico-semantic associations (Ditman & Kuperberg, 2007; Kuperberg, Sitnikova, Goff, & Holcomb, 2006; Swaab et al., 2013; Titone, Levy, & Holzman, 2000, and see Kuperberg, 2010b, for a review), as support for the second theory. However, because language comprehension is highly incremental, with each incoming word being integrated into a high-level discourse representation in real time, it is possible that apparent impairments in using higher-level discourse context could actually arise from a difficulty building this context in the first place, due to impaired lower-level processing.

The present study was designed to distinguish between these two theories by examining how people with schizophrenia interpret ambiguous sentences. Ambiguity resolution is a critical component of everyday language comprehension: To understand a sentence, listeners constantly have to resolve a series of ambiguous sounds, words, and meanings. Here, we focused on one particularly common type of ambiguity -- syntactic ambiguities such as "*wave to the man with the flag",* where the flag could be held by the man or by the waver. Syntactic ambiguity resolution provides an ideal test case for understanding the effects of bottom-up and top-down interactive processes. This is because syntax is often assumed to lie at an intermediate level on the linguistic hierarchy: it may lie above lower-level representations such as *prosody* or *lexical information*, which are therefore said to interact with syntax in a bottom-up fashion. However, it lies below higher-level representations such as *discourse* and *pragmatics,* which are therefore said to interact with syntax in a top-down fashion (see Table 1 for definitions). Here, we asked how people with schizophrenia used these two types of lower-level information in a bottom-up fashion, and these two types of higher-level information in a top-down fashion, to influence syntactic ambiguity resolution, and hence interpretation.

Level of representation examined	Specific manipulation used to influence interpretation	Example of condition that biased towards the Instrument interpretation	Example of condition that biased away from the Instrument interpretation
Prosody: The rhythm and melody of an utterance.	*Prosodic phrasing*: Varying the placement of a pause (…) within the spoken instruction.	"Poke the frog… with the feather."	"Poke…the frog with the feather."
Lexical information: Linguistic information and constraints of individual words.	*Semantic-thematic verb constraints:* Varying the specific verb used in the spoken instruction.	"Poke the frog with the feather."	"Sing to the frog with the feather."
Pragmatics: Information within the broader environment that influences the use and interpretation of language.	*Pragmatically-relevant visual context*: Varying the number of animals in the visual scene that could be referred to by the spoken instruction.	Visual scene contains: (1) A frog holding a feather; (2) a cat holding a flower; (3) a feather.	Visual scene contains: (1) a frog holding a feather; (2) a frog holding a flower; (3) a feather.
Discourse: Information that stretches beyond a single sentence.	*Conversational discourse context:* Varying the type of question appearing before the spoken instruction.	Q: "What should we do to a frog?" A: "Poke the frog with the feather."	Q: "Which frog should we play with now?" A: "Poke the frog with the feather."

Table 1. Definitions of terms and summary of manipulations.

To do this, we used the visual-world eye tracking method, a well-established and well validated psycholinguistics technique that has become a ubiquitous tool for studying the time course of spoken language comprehension (Tanenhaus et al., 1995; Tanenhaus & Trueswell, 2006). Visual-world eye tracking has not been previously used to study schizophrenia, yet it is particularly well suited for this purpose as it provides a naturalistic and minimally demanding experimental analogue to everyday communication. In our paradigm, participants interacted with a set of real-world objects placed in front of them (following Keysar, Barr, Balin, & Brauner, 2000; Sedivy, Tanenhaus, Chambers, & Carlson, 1999; Tanenhaus et al., 1995; and see also Diehl, Friedberg, Paul, & Snedeker, 2015; Gambi, Pickering, & Rabagliati, 2016; Huang & Snedeker, 2009a, 2009b; Snedeker & Trueswell, 2004; Snedeker & Yuan, 2008; Trueswell, Sekerina, Hill, & Logrip, 1999 for work validating this paradigm in populations other than typical adults). For example, participants might see (1) a toy frog holding a small feather, (2) a large feather, (3) a toy cat holding a small flower, and (4) a large flower (see Figure 1). They then listened to spoken instructions telling them how to manipulate these objects, e.g. "*Poke the frog with the feather*". Although this instruction appears simple, it is actually syntactically ambiguous: it can either be interpreted as an instruction to use the large feather as an 'Instrument' to poke the frog (the so-called Instrument interpretation), or to use one's own finger to poke the frog that is holding the small feather. Importantly, there are no 'correct' responses to an instruction like this: its interpretation depends upon how the syntactic ambiguity is resolved, which, in turn, depends upon whether and when participants use different types of informational cues within the context. As participants listen to such instructions, their use of different types of cues can be inferred by examining the pattern of their eye movements to the objects as the spoken verbal input unfolds. For example, if participants infer an instrument interpretation, then they should be more likely to gaze towards the large feather (i.e., the Instrument) when they hear the word "*feather*". Critically, there is little reason to believe that the types of oculomotor process that are measured in the visual world paradigm (i.e., patterns of saccadic eye movements and fixations) are impaired in schizophrenia. Unlike so-called "smooth pursuit" eye movements (Iacono, 1981), there is little evidence that deficits in oculomotor control affect patients' saccades (Whitford et al., 2013).

To assess how participants used lower- and higher-level information to influence their interpretation of these syntactically ambiguous spoken sentences, we separately manipulated four features of the linguistic and non-linguistic input -- two lower-level cues (*prosodic phrasing* see Snedeker & Yuan, 2008, and *semantic-thematic verb constraints*, see Snedeker & Trueswell, 2004), and two higher-level cues (*pragmatically-relevant visual context, see* Tanenhaus et al., 1995, and *conversational discourse information,* see Rabagliati et al., 2014). These manipulations are described, together with definitions and examples, in Table 1. By examining how these cues affected eye movements, we were able to distinguish between the two theories outlined above. The bottom-up theory would predict reduced looks to the Instrument in the schizophrenia group when both lower- and higher-level cues bias towards the Instrument interpretation. The top-down interactive theory, however, would predict reduced looks to the Instrument in the schizophrenia group, only when higher-level cues bias towards this interpretation.

In addition to examining eye movements while participants listened to the sentences, we also examined participants' final actions, reflecting their final interpretations of the sentences. Some previous studies have found that, even though people with schizophrenia can struggle with using different types of cue to process language as it unfolds very quickly, if there is enough time, they can still use such cues to ultimately interpret sentences in similar ways to healthy controls (Ditman & Kuperberg, 2007; Kuperberg, Ditman, & Choi Perrachione, 2018). If this was the case in the present study, then people with schizophrenia and healthy controls might show the same pattern of final actions, even if they showed different patterns of eye movements.

Given the very fast pace of real-world conversation, this would have important psychosocial implications for understanding why some people with schizophrenia struggle with day-to-day social communication.

Methods and Materials

Participants

Twenty-four stable outpatients (3 female) were recruited from the Lindemann Mental Health Center, Boston. All met the DSM-IV-TR criteria for schizophrenia or schizoaffective disorder, confirmed using the Structured Clinical Interview for DSM–IV–TR Axis I Disorders (First, Spitzer, Miriam, & Williams, 2002b). Twenty-two were taking stable doses of antipsychotic medication (19 atypicals; 3 typicals) and two were unmedicated. Symptoms were assessed using the Scale for the Assessment of Positive Symptoms (SAPS, Andreasen, 1984b) and the Scale for the Assessment of Negative Symptoms (SANS, Andreasen, 1984a) either on the day of testing (20 participants) or within 60 days (4 participants), see Table 2. Twenty-four demographically-matched controls (3 female) were recruited by advertisement. Control participants were not taking psychoactive medication and were screened to exclude psychiatric and neurological disorders or substance abuse/dependence (First, Spitzer, Miriam, & Williams, 2002a).

All participants were native English speakers. This study was carried out with the explicit review and approval of the Partners Human Research Committee and Massachusetts General Hospital IRB (#2010P001683) and Tufts Health Sciences Institutional Review Board (#5110). Participants gave written informed consent and were compensated for taking part in the study in accordance with the approved IRB protocols.

Table 2. Demographic, medication and symptom measures.

Note: Means are shown with standard deviations in parentheses. *Premorbid IQ was assessed using the North American Adult Reading Test: NAART (Blair & Spreen, 1989). ^Parental socio-economic status (SES) was calculated using the Hollingshead Index (Hollingshead, 1965). One control and one patient did not provide parental occupation. +Chlorpromazine (CPZ) Equivalents were calculated following the International Consensus Study of Antipsychotic Dosing (Gardner, Murphy, O'Donnell, Centorrino, & Baldessarini, 2010). #SAPS: Scale for the Assessment of Positive Symptoms (Andreasen, 1984b); SANS: Scale for the Assessment of Negative Symptoms (Andreasen, 1984a). SAPS and SANS scores shown are summary scores (sum of the global ratings).

	Control Group	Schizophrenia Group	Comparison between groups
n	24 [3 female]	24 [3 female]	
Age	43 (9)	42 (10)	$t(46)=0.35$, $p=.73$
Premorbid IQ*	96 (9)	93 (11)	$t(46)=1.1$, $p=0.28$
Parental SES^	3.0 (0.8)	2.7 (1.0)	$t(44)=0.78$, $p=.44$
CPZ Equivalent+		394 (293)	
SAPS#		5.1 (3.4)	
SANS#		6.7 (4.3)	

General Procedures

Each participant was tested on three similar experimental tasks examining their use of *prosodic phrasing* (Task 1), the *semantic-thematic constraints of the verb* (Task 2), *pragmatically-relevant visual context* (also in Task 2), and *conversational discourse context* (Task 3). Participants completed the tasks in one of two orders, with Task 2 always second.

We used a "looking while listening" variant of the visual world paradigm in which participants' eye movements were remotely monitored via video-camera and then hand coded (Snedeker & Trueswell, 2004; Snedeker & Yuan, 2008). Participants sat in front of a sloped shelf containing four small platforms (see Figure 1). On every trial, an experimenter placed four different objects on the platforms and named them. These were: (a) the Target Animal: a toy animal holding a small object (e.g., a toy frog holding a small feather); (b) the Target Instrument: a larger object (e.g., a large feather that can be used for poking); (c) the Distractor Animal: another toy animal, either of the same or different type as the Target Animal, holding a different small object (e.g., a different toy frog or a toy cat holding a small flower), and (d) the Distractor Instrument: a different large object (e.g., a large flower).

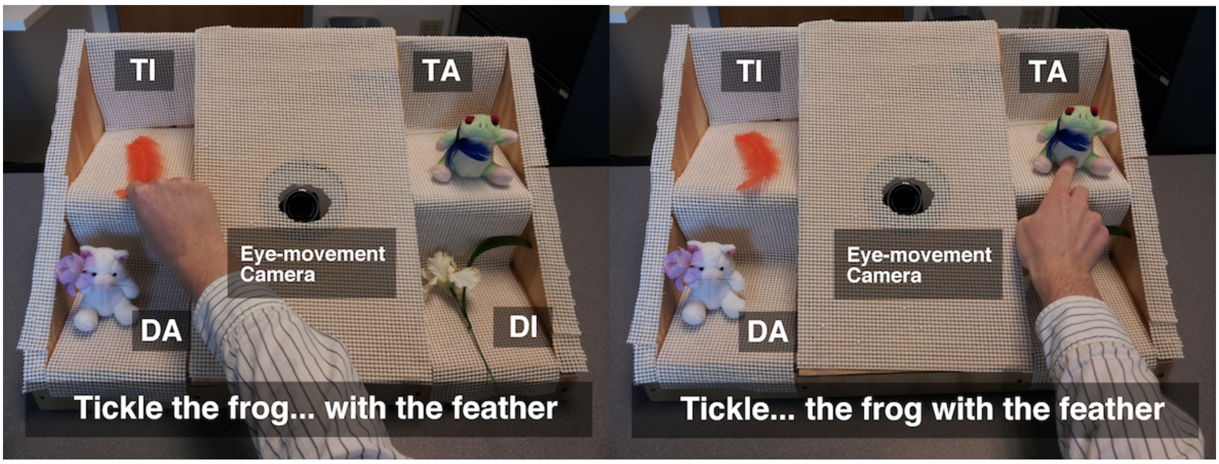

Figure 1. Illustration of the experimental setup used. Left: An action performed with the Target Instrument. Right: An action performed without the Target Instrument. TI = Target Instrument, TA = Target Animal, DI = Distractor Instrument, DA = Distractor Animal.

Participants heard spoken instructions over a loudspeaker (pre-recorded by an unfamiliar female American English speaker). A video camera, embedded in the shelf, recorded the participant's face at 30 frames per second as she/he listened to the instructions; this video was later used to code gaze fixations (see Supplementary materials for full details). A second camera, behind the participant's shoulder, recorded their final actions. Participants were told the purpose of each camera, and that the study was part of a larger project assessing language in children and adults, which explained the somewhat "silly" nature of the instructions.

Each trial used different combinations of animals and instruments. Positions were counterbalanced across trials to avoid learned associations between particular objects and locations. Experimental trials were interspersed with filler trials using a variety of linguistic constructions, animals and instruments.

Task 1: Use of prosodic phrasing. Following Snedeker and Yuan (2008)'s design, we varied how pauses were placed in the experimental instructions, to produce a bias towards the Target Instrument in four experimental trials (e.g., "*You can poke the frog...with the feather"*), and a bias against the Target Instrument in the remaining four experimental trials. (e.g., "*You can poke…the frog with the feather"*). Trials were blocked, such that all four trials from one condition preceded trials from the other and were interspersed amongst 20 filler trials. Scenes always contained animals of different types (e.g., a frog holding a feather and a cat holding a flower).

Task 2: Use of the verb's semantic-thematic constraints and pragmatically-relevant visual information. Following Snedeker and Trueswell (2004)'s design, we varied the particular verb used in the spoken instruction. Eight experimental trials contained verbs that were independently rated (as described by Snedeker and Trueswell, 2004) to probabilistically bias participants towards carrying out an action with an instrument (e.g., "*poke the frog with the feather*"), and eight trials contained verbs like *sing* that bias participants against using the instrument (e.g., "*sing to the frog with the funnel*"). These instructions did not contain any prosodic pauses.

Instructions were crossed with a manipulation of *pragmatically-relevant visual information*. Specifically, we varied the number of potential animal referents of a particular type within the visual scene (Dahan & Tanenhaus, 2004; Snedeker & Trueswell, 2004; Tanenhaus et al., 1995). In eight trials, the scene contained two animals of different types (e.g., a frog and a cat), while in the remaining eight trials, the scene contained two animals of one type (e.g., a frog holding a small feather and another frog holding a small flower). This manipulation works because the latter scene biases away from the Instrument interpretation, as comprehenders who hear "*poke the frog with the feather"* tend to infer that "*with the feather*" disambiguates which of the two frogs should be poked. Experimental trials were randomly interspersed amongst 32 filler trials.

Task 3: Use of conversational discourse information. A question preceded each of the eight experimental trials, asked by a male speaker. In four trials, the question biased participants towards using the Target Instrument (e.g., Question: "*What should we do to a frog?"* Answer: "*Poke the frog with feather"*), and in the remaining four trials, the question biased against using the Target Instrument (e.g., Question: "*Which frog should we play with now?"* Answer: *"Poke the frog with feather").* All experimental trials contained two animals of the same type (e.g., a frog holding a feather and a frog holding a spoon). They were blocked and interspersed among 20 filler trials.

Analysis

Analysis of eye movements. On each trial, hypothesis-blind research assistants used the video to code the direction of each participant's gaze in relation to the particular location of the object for that trial, see Supplementary Materials for full details.

We conducted a pre-planned "time-window" analysis of the eye movements. This analysis focused on whether participants looked at the Target Instrument (e.g., the large feather) at any point within each of two time windows following the onset of each instruction's final word (*feather)* — from 200ms-699ms and from 700ms-1199ms. These time windows were selected *a priori:* they are the same as those analyzed by Snedeker and Trueswell (2004) and Diehl et al. (2015), who used a similar paradigm to assess syntactic ambiguity resolution in healthy adults, adolescents with Autism Spectrum Disorder, and young children. We specifically chose this approach over alternatives such as Growth Curve Analysis (Mirman, Dixon, & Magnuson, 2008), in part because recent work (Huang, Stranahan, & Snedeker, 2017) has suggested that the latter analyses can produce a high rate of false positives, a finding that we have confirmed with our own simulations on the present dataset. In contrast, as well as implementing strong *a prior* hypotheses, the time-window analysis we adopt here also accurately reflects many of the temporal properties of gaze behaviour, including the fact that fixations typically last for many hundreds of milliseconds.

Analyses were carried out using mixed effect logistic regressions fit using lme4 package version 1.1 (Bates, Mächler, Bolker, & Walker, 2015) in R (R Core Team, 2016). We used logistic rather than linear regression because our dependent variable was binary: whether a participant fixated the Target Instrument during each time window, or whether they looked elsewhere (collapsing across looks to one of the other quadrants, to the central fixation point, or off the stage altogether). The linking function for logistic regression thus provides a more accurate model of the data and is better able to account for floor and ceiling effects.

We structured the predictors in our regression to make them maximally comparable to an ANOVA. For each task and population group, we crossed the factors Information bias (cues biasing towards or away from the Instrument interpretation), and Time Window (early or late). In all analyses, we treated subjects as random effects. In Task 2 (where trials were randomly ordered), the effect of Information Bias was treated as a random effect within subjects, but in Tasks 1 and 3, where trials were blocked, Information Bias was simply treated as a fixed effect, to account for the fact that many subjects perseverated on an interpretation (and thus effects could be clearly seen between subjects). Time Window was allowed to vary within subjects. Then, to determine whether effects of Information Bias differed significantly between the control and schizophrenia groups, we also carried out between-group analyses, in which we crossed Group (controls or patients) with Information Bias and Time Window.

To assess the significance of all main effects and interactions involving fixed factors we used Wald tests. We report results for key regression coefficients in the main text; for full regression model results see https://osf.io/bdkpy/.

Analysis of final actions. Hypothesis-blind research assistants coded whether or not participants used the Target Instrument as they acted out each instruction. This indicated whether participants ultimately adopted an "Instrument" interpretation of the instruction. Participants' actions were then analysed using logistic regressions. For each task, we crossed the factors Information bias (cues biasing for or against using the target instrument) and Group (controls or patients). Random effects were treated as above. The full results of all models are available at https://osf.io/bdkpy/.

Results

Analysis of online processing (eye movements)

Effects of prosodic phrasing and verb semantic-thematic constraints. The eye movements of control participants and people with schizophrenia were affected by both prosodic phrasing (Figure 2A) and the verb's semantic-thematic constraints (Figure 2B): both groups appeared to look more often to the Instrument when these bottom-up cues suggested that they should do so (see Table 3 for descriptive statistics).

Logistic regressions confirmed these patterns. In controls, there were significant effects of prosodic phrasing on eye movements (Beta = -0.80(SE = 0.13), CI = [-1.05,-0.55], Wald's z = 6.3, $p<.001$): when prosody biased towards the Instrument interpretation, the odds of gazing at the Target Instrument were significantly higher than when it biased against the Instrument interpretation. Similarly, in people with schizophrenia, the effect was also significant (Beta = -0.74(0.16), CI = [-1.05,-0.43], Wald's z = 4.7, $p<.001$), meaning that people in this group were also more likely to gaze at the Target Instrument when the prosody biased towards this interpretation. A between-group comparison confirmed that the size of the prosody effect did not significantly differ between controls and people with schizophrenia (no interaction between Information Bias and Group, Beta = 0.11(0.20), CI = [-0.28,0.50], Wald's z = 0.53, $p=.59$).

Similarly, in both the control and schizophrenia group, there were significant effects of the verb's semantic-thematic constraints. The control group looked significantly more at the Target Instrument when the verb was biased towards this interpretation (Beta = -0.92(0.16), CI = [-1.23,-0.60], Wald's z = 5.7, $p<.001$), and the same was true for people with schizophrenia (Beta = -0.84(0.19), CI = [-1.20,-0.47], Wald's z = 4.5, $p<.001$). Once again, this effect did not differ significantly between the two groups (Beta = -0.07(0.10), CI = [-0.14,0.28], Wald's z = 0.68, p=.49).

Effects of pragmatically-relevant visual information and conversational discourse information. In contrast to the lower-level cues, the effects of both pragmatically-relevant visual information (Figure 2C) and conversational discourse information (Figure 2D) on eye movements appeared to differ between the control and schizophrenia groups (see Table 3 for descriptive statistics). Whereas controls looked more often to the Target Instrument when both these higher-level cues suggested that they should do so, people with schizophrenia did not appear to show such robust effects.

Logistic regressions confirmed these observations. In controls, the effect of pragmatically-relevant visual context was significant (Beta = -0.39(0.16), CI = [-0.71,-0.07], Wald's z = 2.4, p=.02): when visual context biased towards the Instrument interpretation, controls were more likely to gaze at the Target Instrument. In people with schizophrenia, however, the effect was not significant (Beta = 0.10(0.13), CI = [-0.17,0.36], Wald's z = 0.72, p=.47): visual context did not significantly affect their gaze to the target instrument. The between-group analysis confirmed that visual context had a significantly greater effect on controls than on people with schizophrenia (significant interactions between Information Bias and Group, Beta = 0.21(0.10), CI = [0.02,0.40], Wald's z = 2.1, p=.03).

Similarly, conversational discourse information significantly affected the eye movements of control participants (Beta = -0.58(0.15), CI = [-0.88,-0.28], Wald's z = 3.8, p<.001); they were significantly more likely to gaze at the Target Instrument when the prior question was biased towards this instrument interpretation. In contrast, conversational discourse did not have a significant effect on the eye movements of people with schizophrenia (Beta = -0.1(0.14), CI = [-0.37,0.16], Wald's z = 0.76, p=.45). Once again, the between-group analysis confirmed that the conversational discourse information had a significantly greater effect in controls than in people with schizophrenia (significant interaction between Information Bias and Group, Beta = 0.45(0.20), CI = [0.05,0.84], Wald's z = 2.2, p=.03).

We also carried out exploratory correlational analyses between patterns of eye movements and clinical variables within the schizophrenia group. These are reported in Supplementary Material.

Analysis of final interpretations (final actions)

Both groups of participants made similar use of bottom-up prosodic phrasing and semantic-thematic constraints to inform their final actions (see Figure 2 and Table 3 for descriptive statistics). Logistic regressions confirmed this pattern. When both these bottom-up cues biased towards the Target Instrument, then both control participants and people with schizophrenia were significantly more likely to use the Target Instrument to carry out their final actions, compared to when the phrasing was biased against the Target Instrument. This held for both prosodic phrasing (controls: Beta = -1.1(0.21), CI = [-1.48,-0.64], Wald's z = 4.9, p<.001; people with schizophrenia: Beta = -0.94(0.18), CI = [-1.29,-0.58], Wald's z = 5.2, p<.001) and for the verb's semantic-thematic constraints (controls: Beta = -1.19(0.20), CI = [-1.58,0.81], Wald's z = 6.0, p<.001; people with schizophrenia: Beta = -2.5(0.67), CI = [-3.81,-1.19], Wald's z = 3.74, p<.001). Between-Group analyses revealed no significant differences between the two groups in how these two types of bottom-up information influenced their final actions (no significant interactions between Information Bias and Group for Prosodic Phrasing: Beta = -0.04(0.13), CI = [-0.30,0.21], Wald's z = 0.32, p=.75, or for semantic-thematic constraints: Beta = -0.19(0.15), CI = [-0.53,0.14], Wald's z = 1.1, p=.25).

The pattern for conversational discourse was similar (Figure 2D and Table 3). Both groups used this information to inform their final actions (controls: Beta = -0.42(0.20), CI = [-0.82,-0.02], Wald's z = 2.1, p=.04; people with schizophrenia: Beta = -0.58(0.20), CI = [-0.99,-

0.18], Wald's z = 2.9, p=.004) and there was no significant difference between the two groups (no significant interaction between Information Bias and Group, Beta = -0.09(0.14), CI = [-0.37,0.19], Wald's z = 0.62, p=.54). Interestingly, despite showing an effect on controls' eye movements (see above), pragmatically-relevant visual context (Figure 2C and Table 3) did not significantly affect controls' final actions (Beta = -0.24(0.17), CI = [-0.56,0.09], Wald's z = 1.4, p=.16)[1]. It also did not significantly affect patients' final actions (Beta = -0.10(0.22), CI = [-0.54,0.33], Wald's z = 0.45, p=.65), and there was no between-group difference in these effects (no significant interaction between Information Bias and Group, Beta = 0.04(0.12), CI = [-0.19,0.27], Wald's z = 0.32, p=.75).

[1] It is unclear why control participants did not show this predicted effect, as it has previously been described in both healthy college students and children (Dahan & Tanenhaus, 2004; Snedeker & Trueswell, 2004; Tanenhaus et al., 1995). One possibility is that this null finding is a "false negative". However, it is also possible that the effect of visual information is simply less strong in the population from which our control group was drawn, which differs from these previously-studied populations in a number of demographic ways. Importantly, for the purpose of this study, control participants did show a significant online effect (as indexed by their eye movements), while, as described above, people with schizophrenia failed to show this online effect.

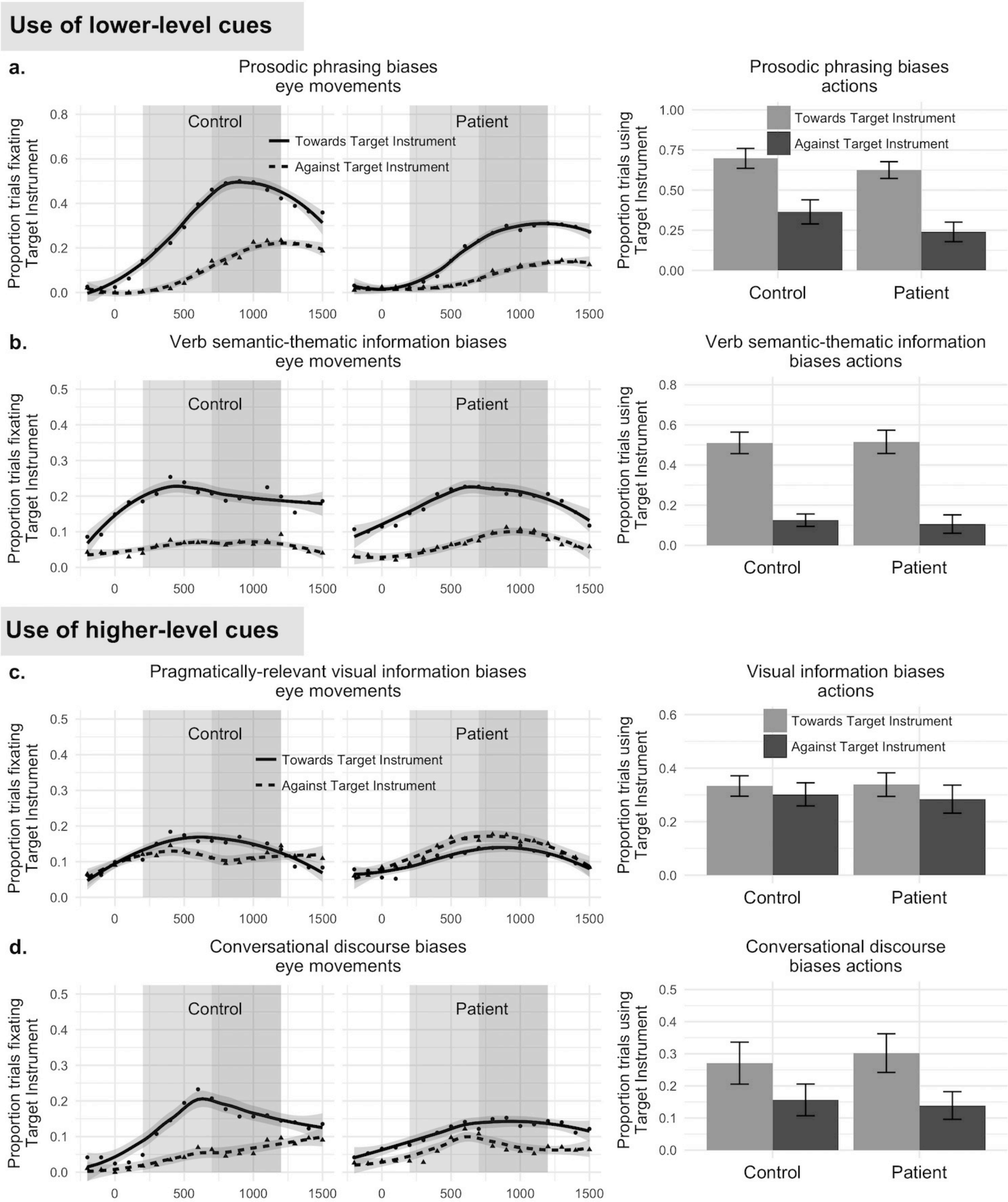

Figure 2. How participants' eye movements and final actions were affected by lower- and higher-level information. (a.) Use of prosodic phrasing, (b.) Use of lexical information, (c.) Use of pragmatically relevant visual information, (d.) Use of conversational discourse information. Graphs show proportion of trials on which controls (left panel) and patients (middle panel)

fixated on the Target Instrument within the early and late time windows, both when information biased towards and against the instrument interpretation. Lines are loess smoothers; shaded ribbons indicate 95% C.I. Right panels show participants' final actions. Error bars represent +/- one standard error of the mean. Supplementary materials show eye movements to each object over time.

Table 3. Mean proportion of trials on which participants fixated the Target Instrument (Early and Late time windows) or used the Target Instrument to carry out their final Actions, depending on whether the different experimental manipulations biased towards or against the Instrument interpretation. Standard deviations are in parentheses.

Manipulation	Population	Target Instrument Bias	Early eye movement window	Late eye movement window	Final actions
Prosodic phrasing	Controls	Towards	0.48 (0.33)	0.68 (0.29)	0.70 (0.30)
		Against	0.14 (0.16)	0.32 (0.25)	0.36 (0.37)
	People with schizophrenia	Towards	0.23 (0.21)	0.40 (0.27)	0.63 (0.26)
		Against	0.06 (0.13)	0.18 (0.24)	0.24 (0.30)
Verb semantic-thematic Information	Controls	Towards	0.36 (0.27)	0.35 (0.20)	0.51 (0.26)
		Against	0.10 (0.11)	0.13 (0.16)	0.13 (0.15)
	People with schizophrenia	Towards	0.34 (0.20)	0.34 (0.24)	0.52 (0.28)
		Against	0.12 (0.16)	0.15 (0.19)	0.11 (0.22)
Pragmatically relevant visual information	Controls	Towards	0.25 (0.16)	0.26 (0.21)	0.33 (0.19)
		Against	0.21 (0.21)	0.21 (0.19)	0.30 (0.21)
	People with schizophrenia	Towards	0.21 (0.16)	0.23 (0.19)	0.34 (0.22)
		Against	0.25 (0.17)	0.26 (0.23)	0.28 (0.26)
Conversational discourse information	Controls	Towards	0.26 (0.31)	0.28 (0.25)	0.27 (0.32)
		Against	0.08 (0.14)	0.16 (0.21)	0.16 (0.24)
	People with schizophrenia	Towards	0.17 (0.18)	0.21 (0.23)	0.30 (0.29)
		Against	0.15 (0.18)	0.18 (0.20)	0.14 (0.21)

Discussion

This study used the visual world eye tracking paradigm to compare how people with schizophrenia and demographically matched healthy controls use two types of lower-level information (prosodic and lexical representations) and two types of higher-level information (pragmatic and discourse representations) to guide syntactic processing during naturalistic spoken language comprehension. We found a dissociation in how the groups use these different types of cues as language is processed. In both groups, eye movements were robustly affected by a sentence's prosodic phrasing, as well as by the lexical constraints of its verb, suggesting that these lower-level cues quickly biased syntactic processing to influence interpretation. However, in comparison with healthy controls, higher-level cues — pragmatically-relevant visual information and conversational discourse information — had a significantly reduced effect on the eye movements of people with schizophrenia, suggesting that they did not use these cues to immediately bias syntactic processing and sentence interpretation. Despite these differences in online processing, the two groups did ultimately reach the same interpretations, as reflected by their final actions.

These findings suggest that people with schizophrenia are impaired in their ability to *predictively* use higher-level information in a highly interactive top-down fashion to inform the *immediate* processing and interpretation of incoming information. Importantly, this cannot easily be explained by a more general cognitive deficit. Such general deficits can sometimes lead to the artificial appearance of a differential deficit because of task demands or performance at ceiling or floor (see Chapman & Chapman, 1973; Gold & Dickinson, 2012). However, our eye tracking paradigm posed essentially no task demands (participants simply needed to interpret simple sentences with no ‘correct’ interpretations)[2], and performance was never at either ceiling or floor in our key measures.

Our findings go beyond prior work in several ways. The demonstration of a dissociation between the use of higher- and lower-level information to process the syntactic structure of an entire sentence extends previous findings reporting similar dissociations between the effects of higher-level discourse and lower-level lexical information on semantic processing of individual words within sentences (Ditman, Goff, & Kuperberg, 2011; Kuperberg et al., 2006; Sitnikova, Salisbury, Kuperberg, & Holcomb, 2002; Swaab et al., 2013; Titone et al., 2000). Our findings also show that this dissociation extends across multiple different higher- and lower-level information sources. Specifically, the same people with schizophrenia who were able to use lower-level lexical information to modulate syntactic processing during real-time comprehension were also able to use lower-level prosodic phrasing. And the same people with schizophrenia who were impaired in their use of higher-level conversational discourse context were also impaired in their use of higher-level pragmatically-relevant visual information. This significantly bolsters claims for a selective impairment of top-down interactive processing in schizophrenia.

Our finding that people with schizophrenia were impaired in their use of non-verbal pragmatic information (i.e., relevant information within the surrounding visual scene) is consistent with other evidence of pragmatic communicative difficulties in schizophrenia (e.g. Bambini et al., 2016; Colle et al., 2013; Harrow, Lanin-Kettering, & Miller, 1989; Meilijson, Kasher, & Elizur, 2004; Pawełczyk, Kotlicka-Antczak, Łojek, Ruszpel, & Pawełczyk, 2017), which may be related to more general theory of mind deficits (Frith, 2004; but see McCabe, Leudar, & Antaki, 2004). This finding also speaks to the precise role of working memory in

[2] Note that this differs from many laboratory tasks and paradigms, such as the Stroop or the AX-CPT, in which the use of top-down information entails the use of specific task-relevant goals to override prepotent bottom-up responses. In such tasks, using ‘top-down’ information is inherently more difficult than using bottom-up information.

language processing: given that participants could always see the visual scene in front of them, the relative insensitivity to this type of information in the schizophrenia group implies that high-level impairments are not solely due to problems in maintaining or manipulating higher-level linguistic information over time within working memory. Rather, they suggest a more specific impairment in the top-down use of goal-relevant information to constrain processing, which may be dissociable from simple maintenance demands in schizophrenia (e.g., see Barch & Smith, 2008; Kim et al., 2004 for discussion).

The key features of our study -- its naturalistic methodology and broad exploration of linguistic context --license a number of novel conclusions. However, it is important to note how inferences from these data should be constrained. For example, one strength of our study was that the same participants completed multiple different tasks, permitting conclusions about patterns of strength and weakness. However, our sample size was comparatively small. This, along with the relatively small proportion of female participants, should be borne in mind when considering the generalizability of our findings, particularly over whether this pattern of results is a stable feature of schizophrenia or whether it evolves over the course of the disorder or through its pharmacological treatment. While we did not find correlations between performance and either age or medication (see Supplement), a definitive answer to this question would require a larger sample size and, ideally, longitudinal data. It will also be important to determine whether a similar dissociation is evident in people at high risk for developing schizophrenia.

Our main finding – eye-movement evidence that individuals with schizophrenia are selectively impaired in their use of higher-level information to predictively and interactively influence processing of bottom-up linguistic input -- is consistent with more general frameworks proposing that a breakdown of predictive mechanisms can explain multiple aspects of the schizophrenia syndrome (Adams, Stephan, Brown, Frith, & Friston, 2013; Corlett et al., 2009; Corlett, Taylor, Wang, Fletcher, & Krystal, 2010; Fletcher & Frith, 2009). Importantly, however, this theory does not imply that higher-level representations are inherently abnormal or that they cannot be used at all in schizophrenia. Rather, it emphasizes a disturbance in the *connections* that allow inputs from higher levels of representation to rapidly and predictively influence processing at intermediate levels of representation, thereby constraining activity from lower levels of representation as they become available (Brown & Kuperberg, 2015). Such fast, online predictive processes are thought to play a critical role in allowing language to be understood quickly and accurately in healthy individuals (Kuperberg & Jaeger, 2016).

Our focus on top-down connections should also not be taken to imply that lower-level perceptual processing is never impaired in schizophrenia, as disturbances in acoustic or lexical processing are well-attested (Cienfuegos, March, Shelley, & Javitt, 1999; Javitt & Freedman, 2015; Kasai et al., 2002). However, our findings raise the interesting possibility that apparent low-level perceptual disturbances may stem from disturbances in top-down predictions (Ford & Mathalon, 2012; Hemsley, 1993; Silverstein et al., 2006; Silverstein, Matteson, & Knight, 1996; see Brown and Kuperberg, 2015, for discussion). This idea also raises the possibility that a breakdown in top-down interactions might actually *cause* lower-level representations to develop abnormally, given the close relationship between prediction and learning in linguistic (Dell & Chang, 2014; Kleinschmidt & Jaeger, 2015; Rabagliati, Gambi, & Pickering, 2015) and non-linguistic (Rescorla, 1988) domains (Adcock et al., 2009; Brown & Kuperberg, 2015). Future longitudinal work will be necessary for understanding the developmental relationship between predictive processing based on higher-level representations and low-level perceptual processing in schizophrenia.

Finally, our finding that patients were impaired in their use of higher-level cues in our naturalistic task has potential implications for understanding the use of spoken language in real-world contexts in schizophrenia. For example, the predictive use of higher-level information plays a vital role in allowing smooth turn-taking during everyday conversational interactions (de

Ruiter, Mitterer, & Enfield, 2006; Magyari & de Ruiter, 2012). It also ensures that language comprehension is fast and accurate in noisy or challenging environments, such as when listening to announcements on public transport or attending to one speaker amongst many in social contexts. Our data shed light on why real-world communication situations like these may present important challenges in schizophrenia (Brown & Kuperberg, 2015). In addition, our finding that, given enough time, patients were able to use these top-down cues to inform their final interpretations (see also Ditman & Kuperberg, 2007; Kuperberg et al., 2018) suggests that, despite such challenges, language deficits may not necessarily manifest using traditional 'off-line' assessment tools. We suggest that the visual world eye tracking method is an ideally naturalistic and well-controlled solution for studying these real-world communication issues in schizophrenia.

Acknowledgments

This work was funded by the National Institute of Mental Health (R01MH071635 to G.R.K.), by the Economic and Social Research Council (ES/L01064X/1 to H.R.), by the National Science Foundation (BCS-0921012 to J.S.) and by a fellowship from the Harvard Mind, Brain, Behavior Initiative (to H.R., G.K., and J.S.).

We are grateful to Donald Goff, Leah Briggs and Claire Oppenheim for supporting patient recruitment, to Paul Mains, Gianna Wilkie, Dan Kim, Kristina Fanucci and Margarita Zeitlin for supporting recruitment and testing, and to Meredith Brown for her comments on the manuscript.

References

Adams, R. A., Stephan, K. E., Brown, H. R., Frith, C. D., & Friston, K. J. (2013). The computational anatomy of psychosis. *Frontiers in Psychiatry, 4*, 47. doi:10.3389/fpsyt.2013.00047

Adcock, R. A., Dale, C., Fisher, M., Aldebot, S., Genevsky, A., Simpson, G. V., . . . Vinogradov, S. (2009). When top-down meets bottom-up: Auditory training enhances verbal memory in schizophrenia. *Schizophrenia Bulletin, 35*(6), 1132-1141.

Andreasen, N. C. (1979a). Thought, language and communication disorders. I. Clinical assessment, definition of terms, and evaluation of their reliability. *Archives of General Psychiatry, 36*, 1315-1321.

Andreasen, N. C. (1979b). Thought, language and communication disorders. II. Diagnostic significance. *Archives of General Psychiatry, 36*, 1325-1330.

Andreasen, N. C. (1984a). Scale for the Assessment of Negative Symptoms (SANS). In. Iowa City: The University of Iowa.

Andreasen, N. C. (1984b). Scale for the Assessment of Positive Symptoms (SAPS). In. Iowa City, IA: The University of Iowa.

Andreasen, N. C. (1986). Scale for assessment of thought, language and communication (TLC). *Schizophrenia Bulletin, 12*, 473-482.

Bambini, V., Arcara, G., Bechi, M., Buonocore, M., Cavallaro, R., & Bosia, M. (2016). The communicative impairment as a core feature of schizophrenia: Frequency of pragmatic deficit, cognitive substrates, and relation with quality of life. *Comprehensive Psychiatry, 71*, 106-120.

Barch, D. M., & Smith, E. (2008). The cognitive neuroscience of working memory: Relevance to CNTRICS and schizophrenia. *Biological Psychiatry, 64*(1), 11-17.

Bates, D. M., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1-48. doi:10.18637/jss.v067.i01

Blair, J. R., & Spreen, O. (1989). Predicting premorbid IQ: A revision of the National Adult Reading Test. *Clinical Neuropsychologist, 3*(2), 129-136. doi:10.1080/13854048908403285

Bleuler, E. (1911/1950). *Dementia Praecox, or the Group of Schizophrenias* (J. Zinker, Trans.). New York: International Universities Press.

Boudewyn, M. A., Carter, C. S., & Swaab, T. Y. (2012). Cognitive control and discourse comprehension in schizophrenia. *Schizophrenia Research and Treatment, 2012*, 484-502. doi:10.1155/2012/484502

Bowie, C. R., & Harvey, P. D. (2008). Communication abnormalities predict functional outcomes in chronic schizophrenia: Differential associations with social and adaptive functions. *Schizophrenia Research, 103*(1-3), 240-247.

Brown, M., & Kuperberg, G. R. (2015). A hierarchical generative framework of language processing: Linking language perception, interpretation, and production abnormalities in schizophrenia. *Frontiers in Human Neuroscience, 9*, 643. doi:10.3389/fnhum.2015.00643

Chapman, L. J., & Chapman, J. P. (1973). Problems in the measurement of cognitive deficit. *Psychological Bulletin, 79*, 380-385.

Cienfuegos, A., March, L., Shelley, A.-M., & Javitt, D. C. (1999). Impaired categorical perception of synthetic speech sounds in schizophrenia. *Biological Psychiatry, 45*(1), 82-88. doi:10.1016/s0006-3223(98)00064-x

Cohen, J. D., & Servan-Schreiber, D. (1992). Context, cortex, and dopamine: A connectionist approach to behaviour and biology in schizophrenia. *Psychological Review, 99*(1), 45-77. doi:10.1037/0033-295x.99.1.45

Colle, L., Angeleri, R., Vallana, M., Sacco, K., Bara, B. G., & Bosco, F. M. (2013). Understanding the communicative impairments in schizophrenia: a preliminary study. *Journal of Communication Disorders, 46*(3), 294-308.

Corlett, P. R., Frith, C. D., & Fletcher, P. C. (2009). From drugs to deprivation: a Bayesian framework for understanding models of psychosis. *Psychopharmacology, 206*(4), 515-530. doi:10.1007/s00213-009-1561-0

Corlett, P. R., Taylor, J. R., Wang, X. J., Fletcher, P. C., & Krystal, J. H. (2010). Toward a neurobiology of delusions. *Progress in Neurobiology, 92*(3), 345-369. doi:10.1016/j.pneurobio.2010.06.007

Dahan, D., & Tanenhaus, M. K. (2004). Continuous mapping from sound to meaning in spoken-language comprehension: immediate effects of verb-based thematic constraints. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*(2), 498-513. doi:10.1037/0278-7393.30.2.498

de Ruiter, J. P., Mitterer, H., & Enfield, N. J. (2006). Projecting the end of a speaker's turn: A cognitive cornerstone of conversation. *Languge, 82*(3), 515-535. doi:10.1353/lan.2006.0130

Dell, G. S., & Chang, F. (2014). The P-chain: relating sentence production and its disorders to comprehension and acquisition. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369*(1634), 20120394. doi:10.1098/rstb.2012.0394

Diehl, J. J., Friedberg, C., Paul, R., & Snedeker, J. (2015). The use of prosody during syntactic processing in children and adolescents with autism spectrum disorders. *Development and Psychopathology, 27*(03), 867-884.

Ditman, T., Goff, D., & Kuperberg, G. R. (2011). Slow and steady: sustained effects of lexico-semantic associations can mediate referential impairments in schizophrenia. *Cognitive, Affective, & Behavioral Neuroscience, 11*(2), 245-258. doi:10.3758/s13415-011-0020-7

Ditman, T., & Kuperberg, G. R. (2007). The time course of building discourse coherence in schizophrenia: An ERP investigation *Psychophysiology, 44*(6), 991-1001. doi:10.1111/j.1469-8986.2007.00565.x

Elman, J. L., Hare, M., & McRae, K. (2004). Cues, constraints, and competition in sentence processing. In *Beyond Nature-Nurture: Essays in Honor of Elizabeth Bates.* (pp. 111-138): Lawrence Erlbaum Associates Publishers, Mahwah, NJ.

Elvevåg, B., Foltz, P. W., Weinberger, D. R., & Goldberg, T. E. (2007). Quantifying incoherence in speech: An automated methodology and novel application to schizophrenia. *Schizophrenia Research, 93*(1-3), 304-316.

First, M., Spitzer, R., Miriam, G., & Williams, J. (2002a). *Structured Clinical Interview for DSM-IV-TR Axis I Disorders, Research Version, Non-patient Edition (SCID-I/NP).* Retrieved from New York:

First, M., Spitzer, R., Miriam, G., & Williams, J. (2002b). *Structured Clinical Interview for DSM-IV-TR Axis I Disorders, Research Version, Patient Edition. (SCID-I/P).* Retrieved from New York:

Fletcher, P. C., & Frith, C. D. (2009). Perceiving is believing: A Bayesian approach to explaining the positive symptoms of schizophrenia. *Nature Reviews Neuroscience, 10*(1), 48-58.

Ford, J. M., & Mathalon, D. H. (2012). Anticipating the future: Automatic prediction failures in schizophrenia. *International Journal of Psychophysiology, 83*(2), 232-239. doi:10.1016/j.ijpsycho.2011.09.004

Frith, C. D. (2004). Schizophrenia and theory of mind. *Psychological Medicine, 34*(03), 385-389.

Gambi, C., Pickering, M. J., & Rabagliati, H. (2016). Beyond associations: Sensitivity to structure in pre-schoolers' linguistic predictions. *Cognition, 157*, 340-351. doi:10.1016/j.cognition.2016.10.003

Gardner, D. M., Murphy, A. L., O'Donnell, H., Centorrino, F., & Baldessarini, R. J. (2010). International consensus study of antipsychotic dosing. *American Journal of Psychiatry, 167*(6), 686-693. doi:10.1176/appi.ajp.2009.09060802

Gold, J. M., & Dickinson, D. (2012). "Generalized cognitive deficit" in schizophrenia: overused or underappreciated? *Schizophrenia Bulletin*, sbs143.

Harrow, M., Lanin-Kettering, I., & Miller, J. G. (1989). Impaired perspective and thought pathology in schizophrenic and psychotic disorders. *Schizophrenia Bulletin, 15*(4), 605-623.

Hemsley, D. R. (1993). A simple (or simplistic?) cognitive model for schizophrenia. *Behaviour Research and Therapy, 31*(7), 633-645. doi:10.1016/0005-7967(93)90116-c

Hollingshead, A. B. (1965). *Two factor index of social position*. New Haven, CT: Yale University Press.

Holshausen, K., Harvey, P. D., Elvevåg, B., Foltz, P. W., & Bowie, C. R. (2014). Latent semantic variables are associated with formal thought disorder and adaptive behavior in older inpatients with schizophrenia. *Cortex, 55*, 88-96. doi:10.1016/j.cortex.2013.02.006

Huang, Y. T., & Snedeker, J. (2009a). Online interpretation of scalar quantifiers: Insight into the semantics-pragmatics interface. *Cognitive Psychology, 58*(3), 376-415. doi:10.1016/j.cogpsych.2008.09.001

Huang, Y. T., & Snedeker, J. (2009b). Semantic meaning and pragmatic interpretation in 5-year-olds: evidence from real-time spoken language comprehension. *Developmental Psychology, 45*(6), 1723-1739. doi:10.1037/a0016704

Huang, Y. T., Stranahan, L., & Snedeker, J. (2017). *Reconsideration on linking eye-movement data with argument realization.* Paper presented at the 39th Annual Meeting of the Cognitive Science Society, London, UK.

Iacono, W. G. (1981). Dissociation of smooth-pursuit and saccadic eye tracking in remitted schizophrenics. *Archives of General Psychiatry, 38*(9), 991. doi:10.1001/archpsyc.1981.01780340043005

Jahshan, C., Wynn, J. K., & Green, M. F. (2013). Relationship between auditory processing and affective prosody in schizophrenia. *Schizophrenia Research, 143*(2-3), 348-353. doi:10.1016/j.schres.2012.11.025

Javitt, D. C. (2009). When doors of perception close: bottom-up models of disrupted cognition in schizophrenia. *Annual Review of Clinical Psychology, 5*, 249-275. doi:10.1146/annurev.clinpsy.032408.153502

Javitt, D. C., & Freedman, R. (2015). Sensory processing dysfunction in the personal experience and neuronal machinery of schizophrenia. *American Journal of Psychiatry, 172*(1), 17-31. doi:10.1176/appi.ajp.2014.13121691

Kantrowitz, J. T., Hoptman, M. J., Leitman, D. I., Silipo, G., & Javitt, D. C. (2014). The 5% difference: early sensory processing predicts sarcasm perception in schizophrenia and schizo-affective disorder. *Psychological Medicine, 44*(1), 25-36. doi:10.1017/S0033291713000834

Kasai, K., Nakagome, K., Itoh, K., Koshida, I., Hata, A., Iwanami, A., . . . Kato, N. (2002). Impaired cortical network for preattentive detection of change in speech sounds in schizophrenia: a high-resolution event-related potential study. *American Journal of Psychiatry, 159*(4), 546-553. doi:10.1176/appi.ajp.159.4.546

Keysar, B., Barr, D. J., Balin, J. A., & Brauner, J. S. (2000). Taking perspective in conversation: The role of mutual knowledge in comprehension. *Psychological Science, 11*(1), 32-38. doi:10.1111/1467-9280.00211

Kim, H., Somerville, L. H., Johnstone, T., Polis, S., Alexander, A. L., Shin, L. M., & Whalen, P. J. (2004). Contextual modulation of amygdala responsivity to surprised faces. *Journal of Cognitive Neuroscience, 16*(10), 1730-1745. doi:10.1162/0898929042947865

Kleinschmidt, D. F., & Jaeger, F. T. (2015). Robust speech perception: Recognize the familiar, generalize to the similar, and adapt to the novel. *Psychological Review, 122*(2), 148-203. doi:10.1037/a0038695

Kreher, D. A., Goff, D., & Kuperberg, G. R. (2009). Why all the confusion? Experimental task explains discrepant semantic priming effects in schizophrenia under "automatic" conditions: Evidence from event-related potentials. *Schizophrenia Research, 111*(1-3), 174-181. doi:10.1016/j.schres.2009.03.013

Kuperberg, G. R. (2010a). Language in schizophrenia Part 1: an Introduction. *Language and Linguistics Compass, 4*(8), 576-589. doi:10.1111/j.1749-818X.2010.00216.x

Kuperberg, G. R. (2010b). Language in schizophrenia Part 2: What can psycholinguistics bring to the study of schizophrenia...and vice versa? *Language and Linguistics Compass, 4*(8), 590-604. doi:10.1111/j.1749-818X.2010.00217.x

Kuperberg, G. R., Ditman, T., & Choi Perrachione, A. (2018). When proactivity fails: An electrophysiological study of establishing reference in schizophrenia. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging, 3*(1), 77-87.

Kuperberg, G. R., & Jaeger, T. F. (2016). What do we mean by prediction in language comprehension? *Language, Cognition, and Neuroscience, 31*(1), 32-59. doi:10.1080/23273798.2015.1102299

Kuperberg, G. R., McGuire, P. K., & David, A. (1998). Reduced sensitivity to linguistic context in schizophrenic thought disorder: Evidence from online monitoring for words in linguistically-anomalous sentences. *Journal of Abnormal Psychology, 107*, 423-434.

Kuperberg, G. R., Sitnikova, T., Goff, D., & Holcomb, P. J. (2006). Making sense of sentences in schizophrenia: electrophysiological evidence for abnormal interactions between semantic and syntactic processing. *Journal of Abnormal Psychology, 115*(2), 251-265. doi:10.1037/0021-843X.115.2.251

Leitman, D. I., Foxe, J. J., Butler, P. D., Saperstein, A., Revheim, N., & Javitt, D. C. (2005). Sensory contributions to impaired prosodic processing in schizophrenia. *Biological Psychiatry, 58*(1), 56-61. doi:10.1016/j.biopsych.2005.02.034

Magyari, L., & de Ruiter, J. P. (2012). Prediction of turn-ends based on anticipation of upcoming words. *Frontiers In Psychology, 3*, 376. doi:10.3389/fpsyg.2012.00376

Mathalon, D. H., Faustman, W. O., & Ford, J. M. (2002). N400 and automatic semantic processing abnormalities in patients with schizophrenia. *Archives of General Psychiatry, 59*(7), 641-648. doi:10.1001/archpsyc.59.7.641

McCabe, R., Leudar, I., & Antaki, C. (2004). Do people with schizophrenia display theory of mind deficits in clinical interactions? *Psychological Medicine, 34*(03), 401-412.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: I. An account of basic findings. *Psychological Review, 88*(5), 375-407. doi:10.1037//0033-295x.88.5.375

Meilijson, S. R., Kasher, A., & Elizur, A. (2004). Language performance in chronic schizophrenia. *Journal of Speech Language and Hearing Research, 47*(3), 695. doi:10.1044/1092-4388(2004/053)

Minzenberg, M. J., Ober, B. A., & Vinogradov, S. (2002). Semantic priming in schizophrenia: A review and synthesis. *Journal of the International Neuropsychological Society, 8*(5), 699-720.

Mirman, D., Dixon, J. A., & Magnuson, J. S. (2008). Statistical and computational models of the visual world paradigm: Growth curves and individual differences. *Journal of Memory and Language, 59*(4), 475-494.

Pawełczyk, A., Kotlicka-Antczak, M., Łojek, E., Ruszpel, A., & Pawełczyk, T. (2017). Schizophrenia patients have higher-order language and extralinguistic impairments. *Schizophrenia Research*.

R Core Team. (2016). R: A language and environment for statistical computing. Vienna, Austria: ISBN 3-900051-07-0.

Rabagliati, H., Gambi, C., & Pickering, M. J. (2015). Learning to predict or predicting to learn? *Language, Cognition and Neuroscience, 31*(1), 94-105. doi:10.1080/23273798.2015.1077979

Rescorla, R. A. (1988). Pavlovian conditioning: It's not what you think it is. *American Psychologist, 43*(3), 151.

Revheim, M. E., Hole, K. H., Bruland, O. S., Reitan, E., Bjerkehagen, B., Julsrud, L., & Seierstad, T. (2014). Multimodal functional imaging for early response assessment in GIST patients treated with imatinib. *Acta Oncologica, 53*(1), 143-148. doi:10.3109/0284186X.2013.798428

Rumelhart, D. E., & McClelland, J. L. (1982). An interactive activation model of context effects in letter perception: II. The contextual enhancement effect and some tests and extensions of the model. *Psychological Review, 89*(1), 60-94. doi:10.1037/0033-295x.89.1.60

Sedivy, J. C., Tanenhaus, M. K., Chambers, C. G., & Carlson, G. N. (1999). Achieving incremental semantic interpretation through contextual representation. *Cognition, 71*(2), 109-147. doi:10.1016/s0010-0277(99)00025-6

Silverstein, S. M., Hatashita-Wong, M., Schenkel, L., Wilkniss, S., Kovács, I., Fehér, A., . . . Savitz, A. (2006). Reduced top-down influences in contour detection in schizophrenia. *Cognitive Neuropsychiatry, 11*(2), 112-132. doi:10.1080/13546800444000209

Silverstein, S. M., Matteson, S., & Knight, R. A. (1996). Reduced top-down influence in auditory perceptual organization in schizophrenia. *Journal of Abnormal Psychology, 105*(4), 663-667.

Sitnikova, T., Salisbury, D. F., Kuperberg, G. R., & Holcomb, P. J. (2002). Electrophysiological insights into language processing in schizophrenia. *Psychophysiology, 39*(6), 851-860.

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. doi:10.1016/j.cogpsych.2004.03.001

Snedeker, J., & Yuan, S. (2008). Effects of prosodic and lexical constraints on parsing in young children (and adults). *Journal of Memory and Language, 58*(2), 574-608. doi:10.1016/j.jml.2007.08.001

Spitzer, M., Braun, U., Hermle, L., & Maier, S. (1993). Associative semantic network dysfunction in thought-disordered schizophrenic patients: Direct evidence from indirect semantic priming. *Biological Psychiatry, 34*, 864-877. doi:10.1016/0006-3223(93)90054-H

Swaab, T. Y., Boudewyn, M. A., Long, D. L., Luck, S. J., Kring, A. M., Ragland, J. D., . . . Carter, C. S. (2013). Spared and impaired spoken discourse processing in schizophrenia: effects of local and global language context. *Journal of Neuroscience, 33*(39), 15578-15587. doi:10.1523/jneurosci.0965-13.2013

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*(5217), 1632-1634. doi:10.1126/science.7777863

Tanenhaus, M. K., & Trueswell, J. C. (2006). Eye movements and spoken language comprehension. In M. J. Traxler & M. A. Gernsbacher (Eds.), *Handbook of Psycholinguistics* (2 ed., pp. 863-900). Oxford: Oxford University Press.

Titone, D., & Levy, D. L. (2004). Lexical competition and spoken word identification in schizophrenia. *Schizophrenia Research, 68*(1), 75-85.

Titone, D., Levy, D. L., & Holzman, P. S. (2000). Contextual insensitivity in schizophrenic language processing: Evidence from lexical ambiguity. *Journal of Abnormal Psychology, 109*(4), 761-767.

Trueswell, J. C., Sekerina, I., Hill, N. M., & Logrip, M. L. (1999). The kindergarten-path effect: studying on-line sentence processing in young children. *Cognition, 73*(2), 89-134.

Whitford, V., O'Driscoll, G. A., Pack, C. C., Joober, R., Malla, A., & Titone, D. (2013). Reading impairments in schizophrenia relate to individual differences in phonological processing and oculomotor control: Evidence from a gaze-contingent moving window paradigm. *Journal of Experimental Psychology: General, 142*(1), 57-75. doi:10.1037/a0028062

Whitford, V., O'Driscoll, G. A., & Titone, D. (2017). Reading deficits in schizophrenia and their relationship to developmental dyslexia: A review. *Schizophrenia Research*.