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Normal categorical perception to syllable-like stimuli in long term and in first episode schizophrenia

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A B S T R A C T

Schizophrenia is associated with deficits in language processing that are evident even at first-episode. However, there is debate as to how early in the processing stream the linguistic deficits appear. We measured categorical processing of artificial syllables that varied in voice-onset time (VOT), and how sensory biasing impacts categorical perception. VOT varied in 5 ms increments from 0 ms (strong /ba/) to 40 ms (strong /pa/). Participants chose whether a syllable sounded more like /ba/ or /pa/. Twenty-two individuals with long-term schizophrenia (Sz) were compared to 21 controls (HCSz), and 17 individuals at their first-episode of schizophrenia (FE) were compared to 19 controls (HCFE). There were three conditions: equiprobable – each syllable had an equal probability of being presented; /ba/−biased – 0 ms VOT (strong /ba/) presented 70% of the time; /pa/−biased – 40 ms VOT (strong /pa/) presented 70% of the time. All groups showed categorical perception and category shifts during biased conditions. Sz and FE were statistically indistinguishable from controls in the point of categorical shift, slope of their response function, and the VOT needed to reliably perceive /pa/. Together, this suggests intact ability to map acoustic stimuli to phonetic categories when based on timing differences in voiced information, both early and late in the disease.

1. Introduction

Schizophrenia is associated with abnormal language processing, including difficulties with comprehension (Tan et al., 2016) and speech production (Perlini et al., 2012), which are related to formal thought disorder (Tan et al., 2015) and low-level perceptual deficits (Brown and Kuperberg, 2015). These deficits are present even at first-episode, where individuals show deficits in abilities such as speech recognition (Wu et al., 2012), and semantic processing (Ferri et al., 2012), which is related to reduced lateralization in fMRI responses when completing language-related tasks (Bleich-Cohen et al., 2009; van Veelen et al., 2011) and decreased grey matter volume (Sheng et al., 2013; Kasai et al., 2003). However, there is debate as to how early in the language processing system the abnormality lies.

Other populations who show difficulties in processing language generally show abnormal processing for even simple linguistic stimuli, such as syllables. For example, individuals with dyslexia show worse syllable discrimination (Pennala et al., 2013) and reduced mismatch negativity (MMN; an event-related potential signaling deviance detection; Dehaene-Lambertz, 1997) to deviant /ga/ syllables compared to standard /da/ syllables (Schulte-Körne et al., 2001). Similarly, individuals with autism show greater latency delay of the mismatch field (the magnetic counterpart of MMN) in left hemisphere to /a/ and /o/ syllables (Kasai et al., 2005), suggesting language-specific deficits in processing syllable deviants (Shestakova et al., 2002).

Indeed, individuals with long-term schizophrenia also have abnormal syllable processing (Cienfuegos et al., 1999; Kugler and Caudrey, 1983) and abnormal MMN/MMF to deviant syllables (Yamasue et al., 2004; Kasai et al., 2002, 2003; Fisher et al., 2008), with MMN deficits being associated with worse verbal memory (Kawakubo et al., 2006) and smaller planum temporale (Yamasue et al., 2004). However, when focusing just on the behavioral measures of syllable processing, there are some discrepancies as to whether individuals with schizophrenia are impaired. Kugler and Caudrey (1983) and Bruder et al. (2001) found poorer accuracy in schizophrenia compared to controls when discriminating between two syllables (/pa/, /ba/, /ta/, /da/, /ka/, and /ga/). Kayser et al. (2001) found reduced hit rate and slower and more variable reaction times in schizophrenia when detecting infrequent deviant syllables (/da/, /ta/, or /ka/ when one of the other syllables

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was the standard). However, Fisher et al. (2008, 2010) found no significant differences in identifying deviant syllables between /a/ and /o/, despite finding reduced MMN in the schizophrenia group. Similarly, Dale et al. (2010) found no significant difference in discrimination accuracy between /ba/ and /pa/ syllables in schizophrenia, despite finding abnormal N100 responses to repeated syllables.

Despite these discrepancies, few studies have systematically measured syllable categorical perception in schizophrenia. Cienfuegos et al. (1999) artificially interpolated the formant frequencies and bandwidths of /ba/ syllables so that the altered syllable is perceived as a /da/. They found that healthy controls showed categorical rather than linear perception, reflected in a steep categorical shift from /ba/ to /da/. However, individuals with long-term schizophrenia showed more linear responses demonstrating weaker categorical processing of linguistic information and/or more graded responses that track the physical changes in the stimuli.

In the current study, we also measured syllabic categorical perception in individuals with long-term schizophrenia, and extended the investigation to measure categorical perception in individuals who were at their first-episode of schizophrenia. We chose to compare those early and late in the disease course to ascertain if any deficits in syllable categorization worsened with disease duration. There are no known studies to focus on syllable processing early in the disease course. It is possible that syllable processing deteriorates with disease progression and comparing those early and late in the disease course will highlight any deterioration.

In this study, we focused on the perception of syllables that varied in their voice-onset time (VOT), specifically /ba/ and /pa/ syllables. VOT is defined as the time between the start burst of the syllable and the onset of voicing (Lisker and Abramson, 1964), or the vibration of the larynx. VOT is considered to be a fundamental unit of language processing (Halle, 1962; Jakobson et al., 1951) that is present across multiple languages (Lisker and Abramson, 1967), and can even be detected by young infants (Eimas et al., 1971). Syllables with short VOTs are perceived as a /ba/. Increasing the VOT creates a categorical shift where the syllable sounds like a /pa/ (Soli, 1983). Perception of VOT depends on reliable timing, and there is some evidence that individuals with schizophrenia exhibit deficits in timing that may be related to language processing (Dale et al., 2010). Focusing on categorization of /ba/ and /pa/ syllables will help examine fundamental language processing and the contribution of any timing deficits in schizophrenia.

Strong categorical processing is expected to produce a steep categorization curve, and floor/ceiling performance at the VOT extremes. VOT category shifts can be influenced by adaptation – repeated presentations of the same stimulus – so that when a new stimulus is presented, it is more likely to be perceived as a member of the other category (Eimas and Corbit, 1973). Therefore, a systematic investigation of the categorical perception of syllables that vary in their VOT from /ba/ to /pa/ in those who are early and late in the disease course will help ascertain which factors of syllabic processing are spared and which are impaired.

2. Materials and methods

2.1. Participants

All participants were recruited from Western Psychiatric Institute and Clinic (WPIC) inpatient and outpatient services. We examined two cohorts of individuals cross-sectionally along the disease course of schizophrenia. All subjects had normal hearing as assessed by audiometry, at least nine years of schooling, and an estimated IQ over 85. None of the participants had a history of concussion or head injury with sequelae, history of alcohol or drug addiction, or detox in the last five years. All participants provided informed consent, and were paid for participation. All procedures were approved by the University of Pittsburgh IRB (PRO12060481), and complied with APA ethical standards.

2.2. Long term schizophrenia (Sz)

Twenty-two individuals with long-term schizophrenia (Sz) were compared with 21 healthy controls (HCSz). Groups were matched for age, gender, Wechsler Abbreviated Scale of Intelligence (WASI) IQ, and parental socioeconomic status. Fifteen Sz had a diagnosis of schizophrenia (residual = 3, undifferentiated = 9, paranoid = 3), and seven had a diagnosis of schizoaffective disorder (depressed = 6, bipolar = 1). All Sz had at least five years of illness or were hospitalized at least three times for psychosis. Two Sz (9%) were unmedicated. The four-factor Hollingshead Scale was used to measure socioeconomic status (SES) in participants and in their parents.

2.3. First episode schizophrenia-Spectrum (FE)

Seventeen individuals at their first-episode of schizophrenia-spectrum disorder (FE) were compared to 19 matched healthy controls (HCFE). Eight FE had a diagnosis of schizophrenia (paranoid = 7, undifferentiated = 1), three schizophreniform disorder, five psychotic disorder NOS, and one schizoaffective disorder (depressed subtype). FE participated if they had accumulated less than two months of lifetime antipsychotic medication exposure. Six FE (35%) were unmedicated. For those who were on antipsychotic medication, FE were on significantly lower doses compared to Sz ($t(20) = 2.38$, $p = .027$).

2.4. Diagnostic assessments

Diagnosis was based on the Structured Clinical Interview for DSM-IV (SCID-P; First et al., 2002). Symptoms were rated using the Positive and Negative Symptom Scale (PANSS; Kay et al., 1987), Scale for Assessment of Positive Symptoms (SAPS; Andreasen, 1984), and Scale for Assessment of Negative Symptoms (SANS; Andreasen, 1981). All tests were conducted by an expert diagnostician.

FE and Sz were compared on their diagnostic scores. FE scored higher on total PANSS scores ($t(34) = 2.66$, $p = .012$), specifically, higher on positive symptoms in the PANSS ($t(34) = 2.84$, $p = .007$). FE also scored higher on the SAPS global ($t(34) = 2.94$, $p = .006$) and item scales ($t(34) = 3.18$, $p = .004$), mirroring the PANSS scores.

2.5. Neuropsychological tests

All participants completed the MATRICS Cognitive Consensus Battery (MCCB; Nuechterlein and Green, 2006) and the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999). Social functioning was assessed with the Global Functioning Scale (GFS, Auther et al., 2006). See Table 1 for neuropsychological test scores.

FE and Sz were statistically similar on all neuropsychological measures, except for the GFS measures of role ($t(34) = 2.97$, $p = .005$), with FE performing better in daily roles such as at work or in relationships.

2.6. Procedure

Synthetic stimuli on a /ba/−/pa/ continuum were provided by Bob McMurray from the University of Iowa (McMurray et al., 2002). These stimuli have been validated previously for inducing categorical perception of /ba/ or /pa/ despite the linear increase in VOT (see Fig. 1 for the signal waveforms of the two extreme VOT syllables). All stimuli were presented using the Psychtoolbox extension in MATLAB. Binaural auditory stimuli were presented over Etymotic 3A insert earphones, with loudness confirmed by a sound meter (75 dB). Participants were presented with nine artificial syllables varying in 5 ms increments of voice-onset time (VOT) along the /ba/−/pa/ continuum. Stimulus

Table 1
Demographic and diagnostic information for the Sz, HCSz, FE, and HCFE groups in condition 1 (equiprobable condition), with t/chi-square statistics and *p*-values for group comparisons. Significant differences between groups are highlighted in bold. Medication is listed in chlorpromazine (CPZ) equivalents. Dosages primarily from Andreasen et al. (2010), and remaining dosages from Gardner et al. (2010).

	Sz	HCSz	Statistics	FE	HCFE	Statistics
N	20	20		17	19	
Age	37.46 ± 8.20	36.72 ± 10.35	$t(38) = 0.25, p = .804$	21.43 ± 3.97	24.98 ± 8.82	$t(25.6) = 1.59, p = .125$
Gender (M/F)	11/9	14/6	$x^2(1) = 0.96, p = .327$	12/5	12/7	$x^2(1) = 0.22, p = .637$
Handedness (R/M/L)	19/1/0	16/0/3	$x^2(2) = 5.26, p = .154$	16/1/0	17/0/2	$x^2(2) = 2.93, p = .231$
IQ	108.25 ± 13.81	102.50 ± 11.34	$t(38) = 1.44, p = .158$	111.35 ± 13.30	110.47 ± 8.55	$t(34) = 0.24, p = .813$
SES	37.20 ± 14.83	36.70 ± 13.86	$t(38) = 0.11, p = .913$	29.18 ± 11.53	37.47 ± 11.66	$t(34) = 2.14$, $\mathbf{p = .039}$
Parental SES	35.42 ± 14.01	41.03 ± 11.46	$t(37) = 1.37, p = .179$	46.20 ± 11.97	50.68 ± 10.75	$t(32) = 1.15, p = .259$
MCCB (MATRICS)	20.32 ± 20.07	40.04 ± 26.13	$t(38) = 2.68$, $\mathbf{p = .011}$	38.39 ± 30.23	43.01 ± 19.44	$t(34) = 0.55, p = .585$
GFS (social)	5.70 ± 1.38	8.78 ± 0.34	$t(38) = 9.67$, $\mathbf{p < .001}$	5.82 ± 1.91	8.97 ± 0.11	$t(34) = 5.35$, $\mathbf{p < .001}$
GFS (role)	3.65 ± 2.28	8.75 ± 0.53	$t(38) = 9.76$, $\mathbf{p < .001}$	6.18 ± 2.30	9.00 ± 0.17	$t(34) = 6.78$, $\mathbf{p < .001}$
Medication (CPZ)	366.76 ± 219.96			129.00 ± 172.99		
Length of illness (months)	264.3 ± 286.76			28.53 ± 43.30		
PANSS Total	62.00 ± 12.97			74.76 ± 15.09		
PANSS Positive	14.65 ± 5.36			19.76 ± 5.31		
PANSS Negative	16.00 ± 4.28			17.35 ± 4.83		
SAPS (global items)	3.45 ± 2.95			6.50 ± 2.90		
SAPS (symptom items)	7.50 ± 6.52			16.94 ± 9.68		
SANS (global items)	9.65 ± 2.58			9.50 ± 3.14		
SANS (symptom items)	30.20 ± 8.39			30.00 ± 8.19		

duration was 377 ms. VOT ranged from 0 ms (strong /ba/) to 40 ms (strong /pa/). There were 180 total stimuli with each syllable presented 20 times throughout the experiment. Participants attended to the stimuli and used a keyboard to decide whether the syllable was a /ba/ or /pa/ in a two-alternative force choice task. After the choice was made, there was an inter-stimulus interval of 500 ms.

For the equiprobable condition, each syllable was presented 20 times. For the /ba/ biased condition, 70% of the stimuli were the 0 ms VOT syllables (strong /ba/), and for /pa/ biased condition, 70% of the stimuli were the 40 ms VOT syllables (strong /pa/). The remaining 30% of the stimuli were equally divided across the other 8 VOTs. The equiprobable condition was always presented first, and the order of the /ba/ and /pa/ biased conditions were randomized.

2.7. Data analysis

Due to time constraints, two Sz did not complete the equiprobable condition, and one FE did not complete the biased conditions. Mean responses that did not reach close to floor (20% or less) or ceiling (80% or more) for extreme VOTs were excluded from analysis (assuming perceptual ambiguity). Following these criteria, data from one HCSZ were rejected for guessing in the equiprobable condition, another from the /ba/ biased condition, and two SZ in the /ba/ biased condition. The demographic and clinical information for the 20 Sz, 20 HCSz, 17 FE, and 19 HCFE who participated in condition 1 are shown in Table 1. The information for the 20 Sz, 20 HCSz, 16 FE, and 19 HCFE who participated in condition 2 are shown in Table 2. The information for the 22 Sz, 21 HCSz, 16 FE, and the 19 HCFE who participated in condition 3 are shown in Table 3.

When measuring forced-choice classifications, linear perception (influenced by the VOT) would produce a relatively straight line with a constant slope. Categorical perception would produce a sigmoidal function, with a rapid conversion between categories at a critical VOT. To compare the parameters of the sigmoidal functions, three points were calculated for each individual, using a non-linear squares function to ascertain the fit of the data to a sum-of-squares logistic function: the top asymptote (at what VOT does the participant reliably (>80%) perceive the syllable to sound like a /pa/), the midpoint of the sigmoid (at what VOT does the participant perceive a shift from /ba/ to /pa/), and the gradient of the sigmoid (the amount of VOT needed to complete the shift from /ba/ to /pa/ – strong categorical perception produces a step-like function and results in a small gradient). All analyses were conducted in R using the nls and SSlogis functions.

For a minority of participants, the data did not fit the assumptions of the logistic function due to the asymptote not being completely flat (details listed below for each condition). To address this, the average of the surrounding values was calculated to replace the abnormal response. In the equiprobable condition, this resulted in 5% of the Sz group's data, 5% of the HCSz, 6% of the FE, and 26% of the HCFE group's data being smoothed. For the /ba/ biased condition, 27% of Sz, 19% of HCSz, 6% of

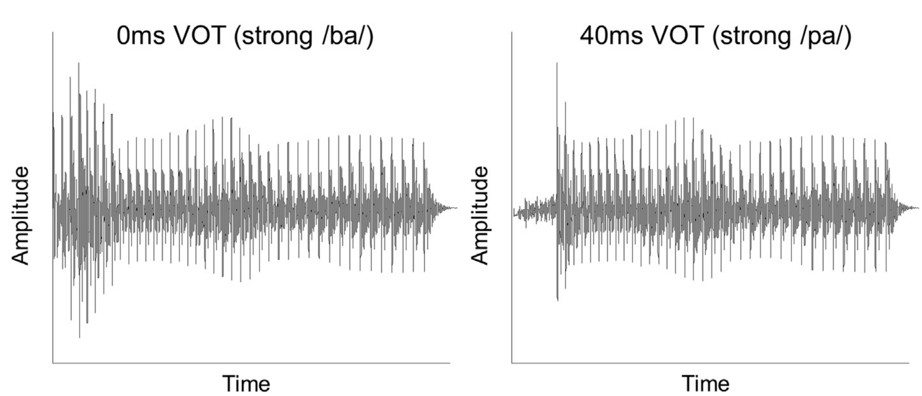

Fig. 1. Signal waveforms of the 0 ms VOT syllable (strong /ba/) and the 40 ms VOT (strong /ba/).

Table 2
Demographic and diagnostic information for the Sz, HCSz, FE, and HCFE groups in condition 2 (/ba/ biased condition), with t/chi-square statistics and p-values for group comparisons. Significant differences between groups are highlighted in bold. Medication is listed in chlorpromazine (CPZ) equivalents. Dosages primarily from Andreasen et al. (2010), and remaining dosages from Gardner et al. (2010).

	Sz	HCSz	Statistics	FE	HCFE	Statistics
N	20	20		16	19	
Age	36.16 ± 6.98	36.72 ± 10.35	$t(3.3) = 0.20, p = .842$	21.15 ± 3.93	24.98 ± 8.82	$t(25.8) = 1.70, p = .100$
Gender (M/F)	13/7	14/6	$x^2(1) = 0.11, p = .736$	12/4	12/7	$x^2(1) = 0.57, p = .452$
Handedness (R/M/L)	19/1/0	16/0/3	$x^2(2) = 5.26, p = .154$	15/1/0	17/0/2	$x^2(2) = 2.89, p = .236$
IQ	108.85 ± 13.25	102.50 ± 11.34	$t(38) = 1.63, p = .112$	111.69 ± 13.67	110.47 ± 8.55	$t(33) = 0.31, p = .761$
SES	36.15 ± 15.12	36.70 ± 13.86	$t(38) = 0.12, p = .905$	29.63 ± 11.75	37.47 ± 11.66	$t(33) = 1.98, p = .056$
Parental SES	35.79 ± 13.90	41.03 ± 11.46	$t(37) = 1.29, p = .206$	46.07 ± 12.41	50.68 ± 10.75	$t(33) = 1.14, p = .263$
MCCB (MATRICS)	19.86 ± 20.42	40.04 ± 26.13	$t(38) = 2.72$, $\boldsymbol{p = .010}$	38.16 ± 31.21	43.01 ± 19.44	$t(33) = 0.54, p = .594$
GFS (social)	5.70 ± 1.45	8.78 ± 0.34	$t(38) = 9.20$, $\boldsymbol{p < .001}$	5.94 ± 1.91	8.97 ± 0.11	$t(33) = 6.34$, $\boldsymbol{p < .001}$
GFS (role)	3,90 ± 2.36	8.75 ± 0.53	$t(38) = 8.97$, $\boldsymbol{p < .001}$	6.25 ± 2.35	9.00 ± 0.17	$t(33) = 4.67$, $\boldsymbol{p < .001}$
Medication (CPZ)	352.08 ± 219.23			137.06 ± 175.33		
Length of illness (months)	260.67 ± 281.20			30.21 ± 44.08		
PANSS Total	62.30 ± 13.08			75.38 ± 15.37		
PANSS Positive	14.80 ± 5.27			19.75 ± 5.48		
PANSS Negative	15.95 ± 4.31			17.79 ± 4.78		
SAPS (global items)	3.65 ± 2.89			6.53 ± 3.00		
SAPS (symptom items)	8.00 ± 6.37			17.33 ± 9.88		
SANS (global items)	9.15 ± 3.28			9.73 ± 3.10		
SANS (symptom items)	31.00 ± 9.00			30.67 ± 8.01		

FE, and 26% of the HCFE data needed to be smoothed. In the /pa/ biased condition, 14% of Sz, 5% of HCSz, 13% of FE, and 21% of the HCFE group needed their data interpolated. Results remained the same when these individuals were excluded from the analysis.

To compare the three parameters of the sigmoid functions (top asymptote, the midpoint of the sigmoid, and the gradient of the sigmoid) between patients and their controls, independent *t*-tests were conducted for each measure. To assess the effect of biasing on the each of the sigmoid parameters, mixed-measures analyses of variance (ANOVA) were conducted: the between-subject comparison was group (Sz and HCSz, or FE and HCFE) and bias (/ba/ biased, equiprobable, /pa/ biased) was the within-subject measure.

To investigate whether there were any differences in reaction times, we conducted mixed-measures ANOVAs for the /ba/ biased, equiprobable, and /pa/ biased conditions separately, with the level of VOT (0-40 ms) as the within-subject measure, and group (Sz and HCSz, or FE and HCFE) as the between-subject measure.

Finally, to assess if there was a relationship between categorical perception and neuropsychological functioning and/or symptoms, Spearman's correlations were conducted. Specifically, measures of the asymptote and the gradient of the sigmoid from the equiprobable condition (condition 1) were correlated with MATRICS and GFS measures, PANSS, SAPS and SANS measures of symptoms, duration of disease and medication, and demographic information (age, IQ, subject SES, and parental SES). To reiterate, larger asymptote values mean that longer VOTs were needed to reliably perceive a /pa/, and greater gradient vales mean that longer VOTs were needed to switch from perceiving a /ba/ to a /pa/. Larger values in both measures indicate more linear/less categorical perception. Correlations with the midpoint of the sigmoid were not conducted as it would be difficult to ascertain what these relationships would mean for categorical perception.

To assess the relationship between the effect of bias on categorical perception and measures of neuropsychological functioning and symptoms, the difference between the asymptote and the midpoint measures in the /ba/ and /pa/ conditions were calculated and used in the correlations. Larger differences in asymptote and midpoint measures indicates a greater effect of biasing. Correlations with the gradient of the sigmoid were not conducted as, once again, significant relationships with differences in gradient would be difficult to interpret. Only significant ($p <$ .05) correlations are reported.

Table 3
Demographic and diagnostic information for the Sz, HCSz, FE, and HCFE groups in condition 3 (/pa/ biased condition), with t/chi-square statistics and p-values for group comparisons. Significant differences between groups are highlighted in bold. Medication is listed in chlorpromazine (CPZ) equivalents. Dosages primarily from Andreasen et al. (2010), and remaining dosages from Gardner et al. (2010).

	Sz	HCSz	Statistics	FE	HCFE	Statistics
N	22	21		16	19	
Age	37.40 ± 7.83	37.36 ± 10.49	$t(41) = 0.17, p = .986$	21.15 ± 3.93	24.98 ± 8.82	$t(25.8) = 1.70, p = .100$
Gender (M/F)	13/9	14/7	$x^2(1) = 0.54, p = .461$	12/4	12/7	$x^2(1) = 0.57, p = .452$
Handedness (R/M/L)	21/1/0	17/0/3	$x^2(2) = 5.59, p = .133$	15/1/0	17/0/2	$x^2(2) = 2.89, p = .236$
IQ	107.59 ± 13.34	101.90 ± 11.38	$t(41) = 1.50, p = .141$	111.69 ± 13.67	110.47 ± 8.55	$t(33) = 0.31, p = .761$
SES	36.27 ± 14.75	36.38 ± 13.59	$t(41) = 0.25, p = .980$	29.63 ± 11.75	37.47 ± 11.66	$t(33) = 1.98, p = .056$
Parental SES	35.24 ± 13.46	40.86 ± 11.19	$t(40) = 1.47, p = .149$	46.07 ± 12.41	50.68 ± 10.75	$t(33) = 1.14, p = .263$
MCCB (MATRICS)	18.50 ± 19/98	40.89 ± 25.77	$t(41) = 3.19$, $\boldsymbol{p = .003}$	38.16 ± 31.21	43.01 ± 19.44	$t(33) = 0.54, p = .594$
GFS (social)	5.77 ± 1.41	8.74 ± 0.37	$t(41) = 9.51$, $\boldsymbol{p < .001}$	5.94 ± 1.91	8.97 ± 0.11	$t(33) = 6.34$, $\boldsymbol{p < .001}$
GFS (role)	3.86 ± 2.29	8.74 ± 0.52	$t(41) = 9.71$, $\boldsymbol{p < .001}$	6.25 ± 2.35	9.00 ± 0.17	$t(33) = 4.67$, $\boldsymbol{p < .001}$
Medication (CPZ)	357.82 ± 211.51			137.06 ± 175.33		
Length of illness (months)	260 ± 273.61			30.21 ± 44.08		
PANSS Total	61.82 ± 12.54			75.38 ± 15.37		
PANSS Positive	14.41 ± 5.17			19.75 ± 5.48		
PANSS Negative	16.05 ± 4.21			17.79 ± 4.78		
SAPS (global items)	3.41 ± 2.87			6.53 ± 3.00		
SAPS (symptom items)	7.36 ± 6.40			17.33 ± 9.88		
SANS (global items)	10.00 ± 3.18			9.73 ± 3.10		
SANS (symptom items)	30.59 ± 8.82			30.67 ± 8.01		

3. Results

3.1. Categorical perception in long term schizophrenia (Sz)

For all three conditions, there were no significant differences between Sz and HCSz in top asymptote (equi: $t(38) = 0.77$, $p = .446$; $d = 0.24$; /ba/ biased: $t(38) = 0.20$, $p = .843$; $d = 0.06$; /pa/ biased: $t(41) = 0.70$, $p = .488$; $d = 0.21$), point of categorical shift (equi: $t(38) = 0.76$, $p = .453$; $d = 0.24$; /ba/ biased: $t(22.2) = 1.52$, $p = .183$; $d = 0.48$; /pa/ biased: $t(41) = 1.20$, $p = .239$; $d = 0.36$), or gradient of the sigmoid (equi: $t(20.8) = 1.33$, $p = .198$; $d = 0.42$; /ba/ biased: $t(38) = 0.38$, $p = .705$; $d = 0.12$; /pa/ biased: $t(41) = 0.14$, $p = .888$; $d = 0.04$; Fig. 2A; left side).

3.2. Categorical perception in First episode schizophrenia-spectrum (FE)

For FE compared to HCFE, there were also no significant differences in top asymptote (equi: $t(34) = 0.61$, $p = .547$; $d = 0.20$; /ba/ biased: $t(33) = 0.85$, $p = .403$; $d = 0.29$; /pa/ biased: $t(33) = 1.20$, $p = .238$; $d = 0.40$), in the gradient of the sigmoid (equi: $t(34) = 0.62$, $p = .539$; $d = 0.21$; /ba/ biased: $t(33) = 0.85$, $p = .403$; $d = 0.04$; /pa/ biased: $t(33) = 0.28$, $p = .779$; $d = 0.10$), or the point of categorical

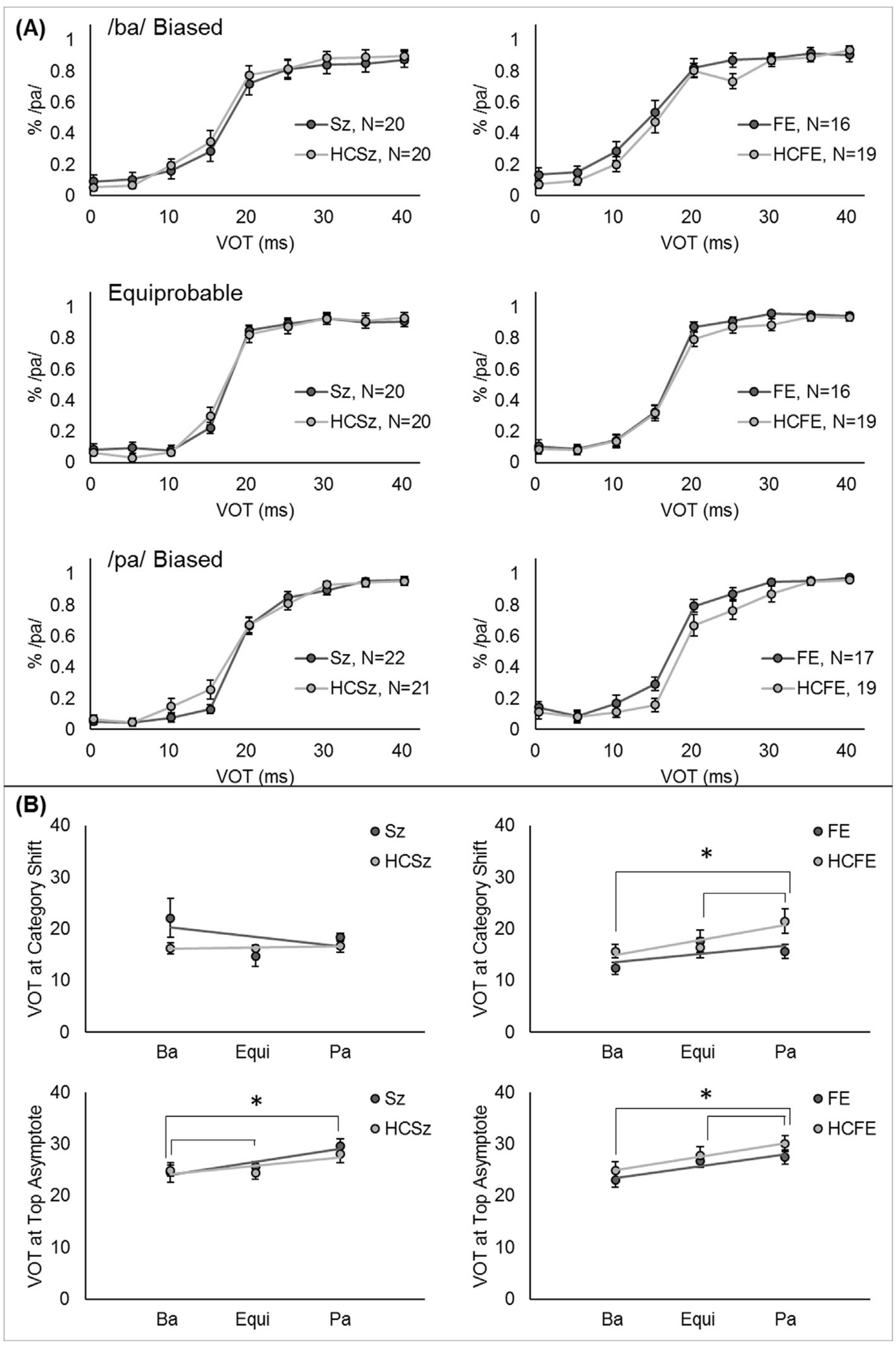

Fig. 2. (A) the sigmoidal response functions from Sz compared to HCSz (left column) and FE compared to HCFE (right column) in the /ba/ biased condition (top row), the equiprobable condition (middle row), and the /pa/ biased condition (bottom row). **(B)** the change in VOT at category shift across the three conditions (top row) and at top asymptote (bottom row) for Sz compared to HCSz (left column) and FE compared to HCFE (right column). Error bars show one standard error. Significant comparisons indicated with asterix.

shift (equi: $t(34) = 0.40$, $p = .695$; $d = 0.13$; /ba/ biased: $t(33) = 1.88$, $p = .069$; $d = 0.64$), except in the /pa/ biased condition, where the HCFE needed longer VOTs to switch from perceiving a /ba/ to a /pa/ as measured by the point of categorical shift ($t(33) = 1.03$, $p = .050$; $d = 0.69$; Fig. 2A; right side).

3.3. Effect of Bias on categorical perception

To ascertain the effect of biasing on categorical perception the point of categorical shift was compared between the three conditions. A repeated-measures ANOVA showed a significant difference between the three conditions ($F(2,150) = 3.19$, $p = .044$; partial $\eta^2 = 0.04$), described by a linear contrast ($F(1,75) = 5.84$, $p = .018$; partial $\eta^2 = 0.07$). Post-hoc comparisons showed that the /pa/ bias produced a significant category shift towards longer VOTs than the /ba/ bias ($p = .018$) and the equiprobable condition ($p = .027$). In other words, the stimuli were more likely to be categorized as a /ba/ than a /pa/, which is typical among healthy listeners. To investigate whether this was consistent for all four groups, the patients were compared to their matched controls in separate mixed-measures ANOVAs. Sz and HCSz did not produce a significant effect of the bias ($F(1.8,65.2) = 2.47$, $p = .097$; partial $\eta^2 = 0.06$), there was no significant difference between groups ($F(1,36) = 0.85$, $p = .362$; partial $\eta^2 = 0.02$) and no significant interaction ($F(1.8,65.2) = 1.69$, $p = .196$; partial $\eta^2 = 0.05$). However, FE and HCFE showed a significant effect of bias ($F(2,66) = 3.63$, $p = .032$; partial $\eta^2 = 0.10$) with significant linear contrasts ($F(1,33) = 8.93$, $p = .005$; partial $\eta^2 = 0.21$) due to the /pa/ bias needing significantly longer VOTs for the category shift than the /ba/ bias ($p = .005$; Fig. 2B; top row). There was no significant difference between the groups ($F(1,33) = 2.19$, $p = .148$; partial $\eta^2 = 0.06$) and no significant interaction ($F(2,66) = 2.31$, $p = .107$; partial $\eta^2 = 0.07$).

For the top asymptote, repeated-measures ANOVA showed a significant effect of bias ($F(2,150) = 13.49$, $p < .001$; partial $\eta^2 = 0.15$) with significant linear contrasts ($F(1,75) = 22.58$, $p < .001$; partial $\eta^2 = 0.22$), due to the /pa/ bias needing longer VOTs to perceive a /pa/ than the /ba/ bias ($p < .001$) or the equiprobable condition ($p < .001$; Fig. 2B). When investigating whether this was the case for all groups, Sz and HCSz produced a significant effect of bias ($F(2,72) = 9.17$, $p < .001$; partial $\eta^2 = 0.20$) with significant linear contrasts ($F(1,36) = 12.46$, $p = .001$; partial $\eta^2 = 0.26$), again due to the /pa/ bias needing longer VOTs to perceive a /pa/ than the /ba/ bias ($p = .001$) or the equiprobable condition ($p < .001$). There was no significant difference between groups ($F(1,36) = 0.32$, $p = .576$; partial $\eta^2 = 0.01$) or significant interaction with the different biasing conditions ($F(2,72) = 0.39$, $p = .676$; partial $\eta^2 = 0.01$). For FE and HCFE, there was also a significant effect of biasing ($F(2,66) = 6.25$, $p = .003$; partial $\eta^2 = 0.16$) with significant linear contrasts ($F(1,33) = 9.69$, $p = .004$; partial $\eta^2 = 0.23$) due to /ba/ needing shorter VOT to perceive a /pa/ than equiprobable ($p = .004$) and the /pa/ bias condition ($p = .020$). Again, there was no significant difference between groups ($F(1,33) = 1.56$, $p = .220$; partial $\eta^2 = 0.05$) and no significant interaction ($F(2,66) = 0.19$, $p = .830$; partial $\eta^2 = 0.01$; Fig. 2B; bottom row).

For the effect of bias on the gradient of the sigmoid, a repeated-measures ANOVA showed no significant difference between the biasing conditions ($F(1.3,44.9) = 0.19$, $p = .731$; partial $\eta^2 < 0.01$), so the group comparisons were not assessed.

To investigate whether there were differences between the patient groups on the effect of bias in categorical perception, Sz and FE were directly compared. There were no significant differences between groups, but there was a significant interaction for the point of categorical shift between group and biasing condition ($F(6,142) = 2.50$, $p = .037$) due to the FE group showing an effect of the bias. All other interactions were not significant. As the two groups differed in age (FE being younger than Sz), age was added as a covariate, and the interaction between group and biasing condition was no longer significant for the point of categorical shift.

3.4. Reaction times and categorical perception

For Sz and HCSz in the equiprobable condition there was a marginal significant main effect of VOT ($F(3.2122.0) = 2.55$, $p = .055$; partial $\eta^2 = 0.06$), with a significant quadratic contrast ($F(1,38) = 15.82$, $p < .001$; partial $\eta^2 = 0.29$) due to participants taking the longest time to decide whether the 15 ms VOT syllable was a /ba/ or a /pa/. There was no significant difference between groups ($F(1,38) = 0.97$, $p = .330$; partial $\eta^2 = 0.03$) and no significant interaction ($F(8,304) = 1.33$, $p = .230$; partial $\eta^2 = 0.03$). For the FE and HCFE groups, there was a significant effect of VOT on reaction times ($F(5.9200.0) = 4.14$, $p = .001$; partial $\eta^2 = 0.11$), with significant quadratic contrasts ($F(1,34) = 4.08$, $p = .051$; partial $\eta^2 = 0.11$), due to participants taking longer to categorize the 15 ms and 20 ms VOT syllables. There was no significant difference between groups ($F(1,34) = 0.22$, $p = .643$; partial $\eta^2 = 0.01$) and no significant interaction ($F(8,272) = 0.92$, $p = .497$; partial $\eta^2 = 0.03$).

For the /ba/ and the /pa/ biased conditions, Sz and HCSz showed a significant effect of VOT on their reaction times (/ba/ biased: $F(3.1118.6) = 3.24$, $p = .023$; partial $\eta^2 = 0.08$; /pa/ biased: $F(4.6, 188.2) = 4.58$, $p = .001$; partial $\eta^2 = 0.10$), due to reaction times being either fastest to the 0 ms VOT syllable in the /ba/ biased condition, or fastest to the 40 ms VOT in the /pa/ biased condition. However, FE and HCFE showed no such effect of VOT (/ba/ biased: $F(4.7155.5) = 0.78$, $p = .559$; partial $\eta^2 = 0.02$; /pa/ biased: $F(1.5,52.1) = 1.22$, $p = .296$; partial $\eta^2 = 0.04$). Again there were no significant group differences or interactions (p's > 0.1).

3.5. Correlations between categorical perception and neuropsychological functioning and symptoms

First, we assessed the relationships between measures of neuropsychological functioning and categorical perception (gradient and asymptote) and between measures of symptoms and categorical perception from the equiprobable condition. Both HCSz and Sz who needed longer VOTs to reach asymptote scored higher on measures of verbal ability in the MATRICS (HCSz: $r(18) = 0.49$, $p = .030$; Sz: $r(18) = 0.53$, $p = .016$), suggesting better verbal ability is associated with more linear/worse categorical perception. Sz who needed longer VOTs to reach asymptote/had worse categorical perception also scored higher on measures of social cognition ($r(18) = 0.45$, $p = .048$) and on overall MATRICS scores ($r(18) = 0.47$, $p = .036$).

HCFE did not produce any significant correlations with measures of categorical perception. FE who had shallower gradients/worse categorical perception had higher activation symptoms on the PANSS ($r(15) = 0.65$, $p = .005$; Fig. 3A).

Next, we assessed the relationship between the bias effect (change in categorical perception [specifically measures of asymptote and the midpoint] between the /ba/ biased and /pa/ biased conditions) and neuropsychological functioning and symptom measures. For HCSz, greater changes in the asymptote/greater effects of bias were associated with worse scores in reasoning and problem solving in the MATRICS ($r(18) = -0.46$, $p = .042$). Sz with higher scores on social measures in the GFS showed greater effect of biasing on the midpoint ($r(18) = 0.45$, $p = .048$), and Sz with faster processing speeds (as measured with the MATRICS) showed greater effects of bias on the asymptote ($r(18) = 0.49$, $p = .028$).

HCFE showed greater effects of bias on the asymptote if they had higher SES and higher IQ (SES: $r(17) = 0.54$, $p = .018$; IQ: $r(17) = 0.56$, $p = .012$). FE showed greater effects of bias on measures of asymptote if they scored higher on activation symptoms from the PANSS ($r(14) = 0.50$, $p = .046$; Fig. 3B).

4. Discussion

Individuals with schizophrenia show deficits in language processing that are apparent even at first-episode. Here we investigated whether

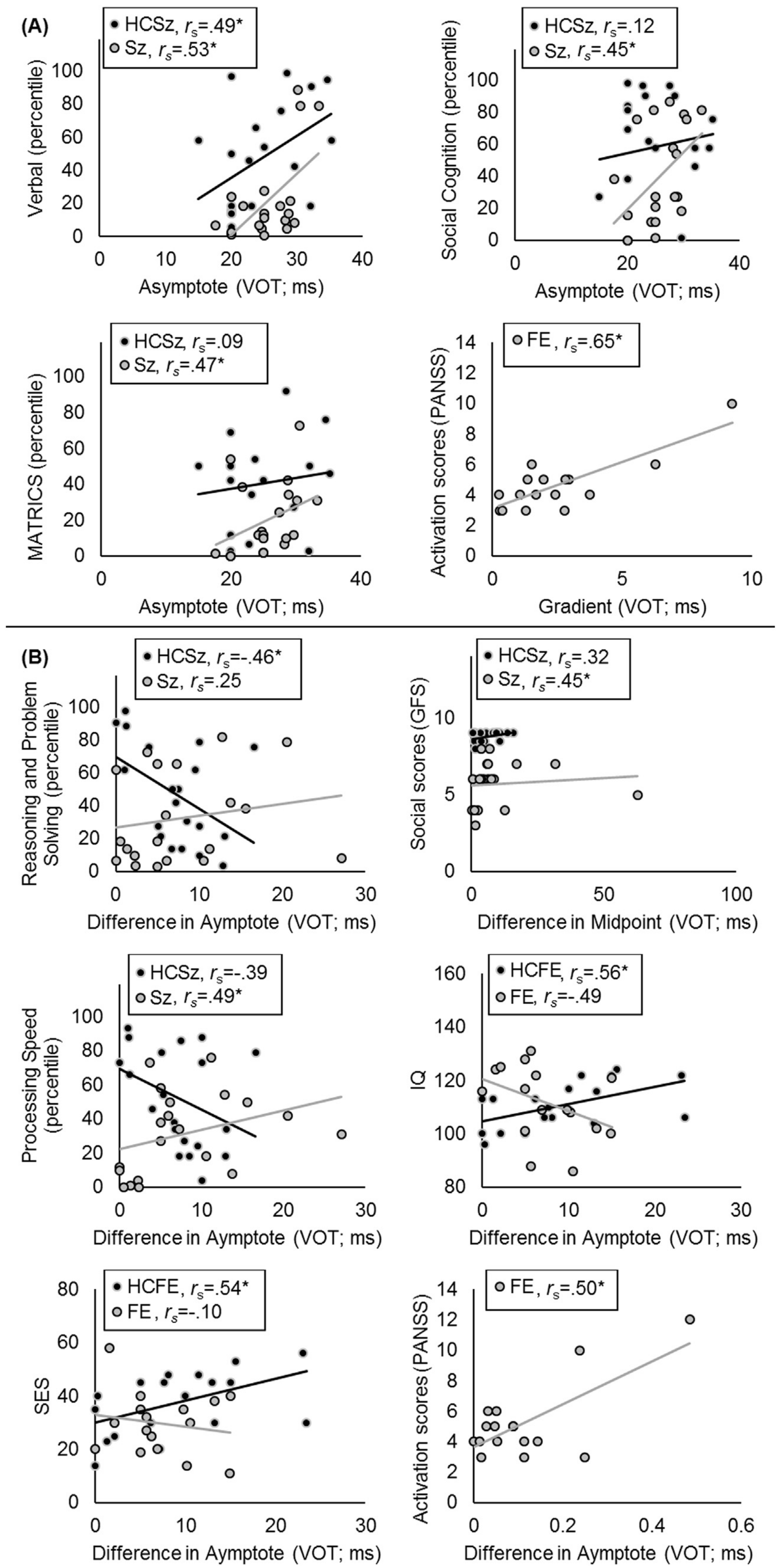

Fig. 3. **(A)** Left to right, top to bottom: correlations between asymptote and verbal, social cognition, and overall MATRICS percentiles in HCSz and Sz, and between gradient and activation scores from the PANSS in FE. **(B)** Left to right, top to bottom: correlations in HCSz and Sz between the difference in asymptote and reasoning and problem solving from the MATRICS, difference in midpoint and social scores from the GFS, and difference in asymptote and processing speed from the MATRICS. Correlations in HCFE and FE between difference in asymptote and IQ and SES. Correlation in FE between difference in asymptote and activation scores from the PANSS.

deficits in language processing were due to problems in the ability to categorize artificial syllables based solely on timing differences. We focused on syllables as they differ phonemically and phonemes are the smallest units of language, representing an early stage of processing in mapping acoustic input to linguistic representations. The syllables presented here varied on one physical dimension – the voice-onset time (VOT) – so that short VOTs were perceived as a /ba/ and long VOTs as a /pa/. If individuals with schizophrenia have deficits in categorical processing, then they should produce shallower (or more linear) sigmoidal functions than controls.

The results show that both individuals with long-term schizophrenia (Sz) and individuals who were at their first-episode of schizophrenia (FE) were as good at categorizing syllables as /ba/ or /pa/ as matched healthy controls: there were no significant differences between groups on the VOT at which the participant perceived the syllable to shift between a /ba/ and a /pa/, no differences in the VOT at which the participant perceived only a /pa/, and no differences in the amount of VOT needed to complete the shift from /ba/ to /pa/. In addition, both patient groups showed effects of biasing (majority /ba/ syllables or majority /pa/ syllables) on the categorical transition point, just like matched control participants. These data provide no evidence for deficits in categorical processing abilities for categorizing syllables based in VOT in schizophrenia, either early or late in the disease course.

There were also no significant group differences in reaction times. For the equiprobable condition, all groups showed slower reaction times to the ambiguous syllables that were around the category boundary, which is consistent with previous studies (Pisoni and Tash, 1974). Sz and HCSz showed effects of the biasing in their reaction times, with faster reaction times to the frequently presented syllables; however, the FE and HCFE did not. FE and HCFE did show consistent effects of biasing in the measures of midpoint and asymptote, whereas Sz and HCSz did not show significant effects of bias in the measure of midpoint. It is therefore possible that there is a trade-off between whether response or speed of response shows the effect of bias.

Several measures of neuropsychological functioning correlated with measures of categorical perception, particularly in the HCSz and Sz groups. However, these findings are highly exploratory and were not corrected for multiple comparisons. If a more conservative alpha of 1% ($p < .01$) is applied to the correlational findings, the only significant correlation remaining was worse categorical perception and higher activation symptoms as measured in the PANSS in FE. The PANSS Activation score comprises Excitement, Tension, and Mannerisms and Posturing. Further studies are needed to explore if and how activation symptoms are related to categorical, and potentially language processing early in the disease course.

It is possible that deficits in categorical perception in schizophrenia are more evident with more complex linguistic stimuli, but not with simple syllables. However, several previous studies found reduced accuracy when categorizing syllables (Kugler and Caudrey, 1983; Bruder et al., 2001; Dehaene-Lambertz, 1997; Kayser et al., 2001; Fisher et al., 2008, 2010), including Cienfuegos et al. (1999) who found that individuals with long-term schizophrenia showed more linear processing of /ba/ and /da/ syllables, using a similar categorization task to the one described here. Therefore, it is unlikely that the simplicity of the stimuli being categorized is responsible for the relatively healthy categorical perception in schizophrenia.

Alternatively, it is possible that individuals with schizophrenia show preserved ability in categorizing syllables that are defined by their VOT. The only study that is known to directly compare behavioral categorization of /ba/ and /pa/ syllables was by Dale et al. (2010) who also reported no significant differences in response accuracy or reaction times. Other studies that have also used /ba/ and /pa/ syllables did so in combination with other syllables /ta/, /da/, /ka/, and /ga/ (Kugler and Caudrey, 1983; Bruder et al., 2010). Both studies reported worse categorization abilities in schizophrenia, but did not separate which syllables were most affected, making it difficult to ascertain whether the discrimination of /ba/ and /pa/ syllables was preserved, or was affected the same as the other syllables.

The other studies that investigated categorical perception in schizophrenia used syllables that differed in their formant frequencies. Cienfuegos et al. (1999) showed more linear processing of /ba/ and /da/ syllables in schizophrenia, and these syllables differ in the onset frequency of their second and third formants (Dehaene-Lambertz, 1997). However, Fisher et al. (2008, 2010) used /a/ or /o/ syllables that differed primarily in their fundamental frequencies but produced no significant differences in accuracy rates. Finally, Kayser et al. (2001) found less accurate responses and slower reaction times in schizophrenia to /da/, /ta/, and /ka/ syllables, which differed in a variety of physical characteristics including fundamental frequency, and formant frequency trajectory at onset, as well as VOT. Therefore, it is possible that individuals with schizophrenia show greater deficits in categorizing syllables based on frequency, but relatively healthy categorization processing of syllables based on VOT. Speculatively, contrasts more reliant upon spectral dimensions like formant frequency trajectory or fundamental frequency may be more severely impacted than contrasts defined across temporal dimensions, like the VOT contrast used in the present study. In support of this possibility, categorization across spectral dimensions results in shallower, less categorical response curves than categorization across temporal dimensions, even in typical listeners (Mirman et al., 2004).

An alternative hypothesis is that VOT distinctions are considered fundamental to speech production across languages (Halle, 1962; Jakobson et al., 1951), and there is evidence to suggest that its ubiquity may be the result of languages capitalizing on a physical limit of the auditory system (Hirsh, 1959) that creates, in auditory processing, a strong categorical boundary. For example, when processing the simultaneity of acoustic events, mammals seem to encode asynchronous onsets as 'simultaneous' so long as the asynchrony is less than about 20 ms, with longer offsets being distinguishable (Holt et al., 2004). VOT operates in a similar way and – across many languages – the VOT boundary is about 20 ms (Keating, 1984). Several studies have also simulated VOT in nonspeech tones (instead of syllables) and found a categorical shift when the tone-simulated asynchrony reached 20 ms (Miller et al., 1976; Pisoni, 1977), similar to the point of category shift shown here between /ba/ and /pa/. As a result of this, some have argued that VOT categorical perception may be a special case that is influenced by sensory discontinuities. If individuals with schizophrenia are spared in this kind of processing, they might show healthy VOT processing, but be impaired when the speech signals require more higher-level processing to accomplish a categorical perception task for other syllables not as well supported by auditory discontinuities.

There are several limitations to this study. The first is that the sample sizes are small. However, the results show strong and reliable categorical perception in all groups including effects of local biasing on categorical perception. Therefore, if any differences in categorical perception exist between individuals with schizophrenia and their matched controls, they must be smaller than the effects of biasing. If categorical processing has a large effect on language processing in schizophrenia, then we would expect to see effects of a similar size to biasing. The second is that we only compared /ba/ and /pa/ categorical processing and so cannot make any generalizations about all syllable categorical perception. It could be that individuals with schizophrenia are sensitive to the subtle changes in timing and they are able to use this as a cue to category processing. Category processing of other syllables such as /da/ and /ga/, or /ra/ and /la/ may be less reliable in schizophrenia as they can be created to depend on other acoustic characteristics such as formant frequency transitions. Third, we cannot generalize beyond categorization of simple syllables. Category perception may be impaired in schizophrenia for more complex linguistic sounds. Further studies exploring category perception in schizophrenia using different stimuli will be able to provide a more complete picture of whether individuals with schizophrenia have deficits in category processing and if this impacts linguistic abilities.

In conclusion, we show no evidence of deficits in the categorical processing of syllables defined by VOT in schizophrenia. Individuals who are at their first episode of schizophrenia and those with long-term schizophrenia both show relatively healthy categorical perception across VOT and normal effects of biasing. Direct comparison of categorical perception to syllables varying in VOT to syllables varying in their formant frequency separation may ascertain whether individuals with schizophrenia are more impaired in categorization across some acoustic stimulus dimensions than others.

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Contributors

Sarah M Haigh designed the protocol, analyzed the data, and wrote the manuscript. Rebecca M Laher helped analyze the data and interpret the results. Timothy K Murphy collected the data and helped analyze and interpret the results. Brian A Coffman helped interpret the results. Kayla L Ward and Justin R Leiter-McBeth collected the data and helped interpret the results. Lori L Holt helped interpret the results and write the manuscript. Dean F Salisbury designed the study, helped interpret the results, and helped write the manuscript. All authors reviewed the final version of the manuscript.

Conflicts of interest

None of the authors have any conflicts of interest to declare.

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