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RESEARCH ARTICLE

Auditory perceptual learning in autistic adults

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Abstract

The automatic retuning of phoneme categories to better adapt to the speech of a novel talker has been extensively documented across various (neurotypical) populations, including both adults and children. However, no studies have examined auditory perceptual learning effects in populations atypical in perceptual, social, and language processing for communication, such as populations with autism. Employing a classic lexically-guided perceptual learning paradigm, the present study investigated perceptual learning effects in Australian English autistic and non-autistic adults. The findings revealed that automatic attunement to existing phoneme categories was not activated in the autistic group in the same manner as for non-autistic control subjects. Specifically, autistic adults were able to both successfully discern lexical items and to categorize speech sounds; however, they did not show effects of perceptual retuning to talkers. These findings may have implications for the application of current sensory theories (e.g., Bayesian decision theory) to speech and language processing by autistic individuals.

Lay Summary: Lexically guided perceptual learning assists in the disambiguation of speech from a novel talker. The present study established that while Australian English autistic adult listeners were able to successfully discern lexical items and categorize speech sounds in their native language, perceptual flexibility in updating speaker-specific phonemic knowledge when exposed to a novel talker was not available. Implications for speech and language processing by autistic individuals as well as current sensory theories are discussed.

KEYWORDS

auditory processing, autism, language development, perceptual flexibility, perceptual learning, phonetic adaptation, speech perception

INTRODUCTION

Talkers vary—and so does their speech. An individual's voice may be referred to as the auditory "face" or "fingerprint" (Belin et al., 2004; Belin et al., 2011). It conveys indexical (e.g., speaker type, stature, age, gender, social, and dialect) and affective information (e.g., emotional state, the speaker's perceived relation with the hearer; Bladon et al., 1984). Perceiving another human's voice depends on an initial set of perceptual abilities and may be affected by both neurological and environmental factors. Over the past several decades, two particular factors (and their amalgamation) have attracted the attention of developmental, neuroscientific, and psycholinguistic research: the processing of voice (i.e., speech), and social interactions. It is not yet clear how people with neurodevelopmental conditions (such as those who are autistic) accommodate the variability of speech caused by talker differences and speech features such as foreign or novel accents, or atypical pronunciations. The current study sought to address this question by assessing phonemic accommodation in autistic adults via an established paradigm for evoking perceptual adaptation of this kind.

During speech perception, listeners are required to perceive and process not only linguistic information but also the acoustic information specific to the interlocutor (Bradlow et al., 1999; Hardison, 2003; Logan et al., 1991; Mullennix & Pisoni, 1990). In addition to other major memory systems, the perceptual representation memory system (Schacter & Church, 1992) is active during perception, particularly perceptual categorization, and aids in the encoding of acoustic characteristics specific to a language and/or talker (such as gender, dialect and speaking rate; Casale & Ashby, 2008; Nygaard & Pisoni, 1998). Listeners' ability to rapidly accommodate the voices of different talkers has been studied extensively (Bladon et al., 1984; Choi et al., 2018; Summerfield & Haggard, 1975; Syrdal & Gopal, 1986; Wong et al., 2004).

In a pioneering two-phase lexically-guided perceptual-learning paradigm, Norris, McQueen, and Cutler (2003) established that perceptual adaptability to the voice of a novel talker occurs efficiently and without difficulty. Exposure to just a few instances of a deviant speech sound (even only 10: Kraljic & Samuel, 2011) induced learning about the specific talker's pronunciation of that sound, as long as the deviant sound occurred in words that were part of listeners' lexical repository. Specifically, in the first phase of Norris et al.'s paradigm, a lexical decision task, two groups of Dutch listeners were exposed to a sequence of naturally-produced real words by an unfamiliar talker, with some items containing an ambiguous fricative between /f/ and /s/ in contexts that favored one interpretation over the other. For one group of listeners, words ending in /f/ (e.g., olijf, "olive") had the sounds replaced by an ambiguous fricative (denoted [?]) midway between /f/ and /s/, while the words ending in natural /s/ remained unchanged. For the other group of listeners, the pattern was reversed: ambiguous /s/, clear /f/ . This created two lexically-guided "training" scenarios. In the immediately following second phase, a categorization task, listeners were presented with and asked to categorize fricatives across an /ɛf-ɛs/ continuum. Listeners who had been exposed to words ending in an ambiguous /f/ tended to categorize an expanded portion of the continuum as /f/, while the opposite pattern was observed for listeners who had been exposed to lexical contexts favoring an /s/-interpretation. A control group exposed to nonwords containing the ambiguous [?] sound showed no bias when asked to categorize the continuum steps as /f/ or /s/. These results suggest that listeners use their lexical knowledge to adapt rapidly and efficiently to idiosyncratic talker pronunciations at the prelexical level.

Perceptual learning effects have been shown to occur automatically, and to be robust and long-lasting. Lexically-guided perceptual learning has been observed across varying populations that include native listeners (for different types of phonemes and other types of speech sounds: McQueen et al., 2006; Mitterer et al., 2013; Sjerps & McQueen, 2010), second language learners (Bruggeman & Cutler, 2020; Burchfield et al., 2017; Cutler et al., 2018; Drozdova et al., 2016), older adults (Scharenborg et al., 2015; Scharenborg & Janse, 2013), 6- and 12-year-old children (McQueen et al., 2012), as well as children with dyslexia (Zhang et al., 2018). However, auditory perceptual-learning effects have not been tested in populations that exhibit atypicalities in communication relative to perceptual, social, and language processing, such as autism.

Autism is characterized by a combination of social and nonsocial features but is most well-known for the way it affects how a person interacts and communicates with others (American Psychiatric Association, 2013). Particularly, autistic people exhibit difficulties in communication and language abilities (Bedford et al., 2013; Eigsti, 2013; Mody & Belliveau, 2013; Simms & Jin, 2015; Whitehouse et al., 2008), which may drive language problems, such as phonological and voice processing (Rapin & Dunn, 1997). In fact, one of the earliest behaviors observed by parents is an autistic child's apparent lack of orienting to speech but not nonspeech sounds (Klin, 1991).

An early apparent "inherent indifference" to speech arises due to temporal processing differences in autistic people (e.g., Allen & Courchesne, 2001; Čeponiene et al., 2003; Gervais et al., 2004), and is related to the severity of autism features (Kuhl, 2004; Kuhl et al., 2005; Sperdin & Schaer, 2016). Findings of atypical brain lateralization, right hemispheric dominance, and reduced activation of left temporal and frontal brain regions have been observed in both autistic children (e.g., Eyler et al., 2012; Lombardo et al., 2015; Redcay, 2008) and adults (e.g., Boddaert et al., 2003; Gervais et al., 2004; Lai et al., 2011). While the reasons for such atypicalities remain unclear, it has recently been claimed that these atypical processing patterns may be driven by alterations in early prenatal development (Adhya et al., 2020).

While perceptual accounts have not been extended to explicitly cover speech processing in the autistic population, theoretical viewpoints account for a "detail-focused style" of information processing (Weak Central Coherence; Frith, 2003; Happé & Booth, 2008; Happé & Frith, 2006), or preference for lower-level processing (Enhanced Perceptual Functioning; Mottron et al., 2006). Specifically, neural coordination required for language processing may be affected by enhanced lower-level perceptual abilities that, in turn, may manifest as early difficulties when tuning to and attending to speech (DePape et al., 2012; Lepistö et al., 2005; Schelinski et al., 2017; Seery et al., 2013). Although empirical findings reveal variability in the processing style and perceptual organization of autistic people (for a review see Evers et al., 2018), research has predominantly concerned how social stimuli are processed, rather than how new speech categories are acquired or whether autistic people show neural plasticity relative to speech category adaptation.

Perceptual category learning requires phonological flexibility and the ability for neural networks to rapidly adapt through repeated experiences (Mercado et al., 2020). Talker adaptation plasticity, in particular, appears to be facilitated by regular language experience involving a variety of novel interlocutors (Bruggeman & Cutler, 2020; Cutler et al., 2019). Specifically, social interactions with multiple talkers are crucial for phonological adaptation and long-term structural maintenance, which may in turn become dormant if not employed regularly (Bruggeman & Cutler, 2020).

However, due to differences in early social interactions compounded by later atypical interactions with others (e.g., Crompton et al., 2020), autistic people show different neural patterns when processing speech (Wang et al., 2017; Yu et al., 2015), and altered perceptual flexibility during speech processing and word recognition (e.g., Happé & Frith, 2014; Stewart et al., 2018; Stewart & Ota, 2008). For instance, adults with elevated autistic traits are less likely to show evidence of top-down lexical processing during speech perception, leading to a reduced "Ganong effect" (Stewart et al., 2018; Stewart & Ota, 2008). Therefore, while the ability to perceive lexical items may very well be intact, a differing interaction between lower-level phonetic and higher-level lexical processing may affect how autistic people adapt existing phoneme categories signaled by lexical differences, compromising perceptual learning.

More recently, computational accounts using Bayesian decision theory (Pellicano & Burr, 2012; Sinha et al., 2014; van Boxtel & Lu, 2013; van de Cruys et al., 2014) have posited that atypicalities in perceptual flexibility and categorical adaptation observed in autistic populations are due to differing neurobiological mechanisms involving prior perceptual experiences (Lawson et al., 2014; Soulières et al., 2011). Neural plasticity involving adaptation and experience-dependent auto-calibration has been observed to result in atypicalities in flexible perceptual processing, specifically in situations involving ambiguity that may in turn affect learning (Pellicano & Burr, 2012; Sinha et al., 2014). In particular, attenuated perceptual flexibility appears to occur in contexts requiring processing of complex or higher-level socially-relevant stimuli, such as an audiovisual recalibration, speech integration, facial and lip-reading (e.g., Karaminis et al., 2015; Magnée et al., 2008; Noel et al., 2017; Turi et al., 2016; Zhou et al., 2021).

A recent review article of speech and language processing in autistic people (Key & D'Ambrose Slaboch, 2021) established that findings of speech processing atypicalities, with no consistent evidence of enhanced sensory processing, could be interpreted through the attenuated flexibility lens (Pellicano & Burr, 2012). However, due to limited and varied samples reported (predominantly in children), it has not been possible to ascertain whether the observed perceptual patterns were reflective of a developmental stage, reduced social interest, or sensory processing characteristic to the autistic endophenotype. Moreover, none of the studies reviewed have been extended to directly examine perceptual adaptation relative to speech processing by autistic adults, who over their lifespan have attained fully-fledged language use and prior social engagement experience.

Therefore, the present study tested whether attenuated adaptation (Pellicano & Burr, 2012), also extends to talker adaptation involving perceptual learning. Specifically, we investigated whether auditory perceptual flexibility differs in autism, and if autistic adults use lexical information to interpret an ambiguous sound as an acceptable exemplar of a native phoneme. Reduced perceptual flexibility would impair a listener's ability to adapt to novel talkers, and diminish the ability to rapidly calibrate and retune phoneme categories. In a perceptual learning experiment, we would observe this as an interaction between participant group (autistic or not) and perceptual learning (relation of exposure and target word pronunciation).

TABLE 1 Demographic information and measures of participants in the autistic and non-autistic groups

Group	Autistic	Non-autistic
	***M* (SD; range) N or frequency**	
N	25	28
Female/male	5/20	22/6
Native language	Australian	English
Diagnosed with autism	25	0
Age of diagnosis		
0–11	20	
12–18	2	
18+	3	
Other diagnoses		
Anxiety	16	11
Depression	8	9
ADHD	8	
Dyslexia	2	1
OCD	3	
Highest level of education		
School certificate	4	
Higher school certificate	9	5
Technical and further education (TAFE) certificate	10	6
Undergraduate (university)	2	9
Postgraduate (university)		8
Currently employed		
Yes	8	24
No	17	4
Previously employed		
Yes	13	26
No	12	2
Average of hours (per week) spent interacting with people outside of immediate circle of family/friends	2.7	18.3

METHOD

Participants

Twenty-five autistic and 28 non-autistic adults completed this experiment. Autistic participants were recruited via autism social community network groups and

TABLE 2 Comparison of the autistic (AUT) and non-autistic (NA) groups in terms of their age, SRS-2, FSIQ-4, VCI and PRI scores, and interaction hours per week

	Group	*N*	Min	Max	*M*	SD	SE	*t*	*p*	*d*
Age in years	AUT	25	17	58	21.84	7.98	1.595	−4.15	<0.001*	1.14
	NA	28	19	48	30.25	6.76	1.278			
SRS-2 score	AUT	25	50	87	67.68	8.72	1.744	8.45	<0.001*	2.32
	NA	28	40	63	48.82	7.53	1.423			
FSIQ-4	AUT	25	94	146	117.40	14.81	2.963	0.488	0.627	0.13
	NA	28	100	131	115.75	9.47	1.790			
VCI	AUT	25	100	160	119.80	16.05	3.210	0.775	0.442	0.21
	NA	28	102	139	117.00	9.85	1.861			
PRI	AUT	25	86	154	110.80	17.21	3.442	0.150	0.882	0.04
	NA	28	94	133	110.21	10.88	2.056			
Interaction hours p/week	AUT	25	1	10	2.72	1.77	0.354	−18.35	<0.001*	4.60
	NA	28	3	20	18.25	3.88	0.734			

Note: Variables included in the group statistics include: Age in years; social responsiveness scale (SRS-2) score; full scale IQ (FSIQ-4); verbal comprehension (VCI); perceptual reasoning (PCI); and hours spent interacting with people outside of their immediate circle of family and friends per week (Interaction hours p/ week). Effect size reported in Cohen's *d* with significant group differences ($p < 0.05$) marked with an asterisk (*).

organizations (e.g., ASPECT). Additional data from two autistic participants were collected but excluded as these participants did not complete the full testing session. All participants reported no hearing difficulties, provided written and verbal informed consent prior to participation, and were paid a small fee (AUD$60) for their participation.

Participants completed a demographic and Language Experience and Proficiency Questionnaire (Marian et al., 2007). All were born and raised in Australia and reported no fluent knowledge of a second language. Non-autistic participants were aged 19–48 years ($M_{age} = 30.25$, SD = 6.76, 22 females) while those in the autistic group were significantly younger ($t[51] = 4.15$, $p = <0.001$, $d = 1.14$), ranging in age between 17 and 58 years ($M_{age} = 21.84$ years, SD = 7.98, 20 males). While we note a discrepancy in gender between participant groups, to date, no empirical evidence suggests gender effects on auditory perceptual learning.

Table 1 presents participants' demographic information. Previous literature has observed social interactions with a variety of talkers to be crucial for phonological adaptation and long-term phonemic structural maintenance (Bruggeman & Cutler, 2020). Here, we asked participants approximately how many hours per week they interact with others outside of their immediate circle of family and friends (autistic: $M = 2.7$ h, SD = 1.77; non-autistic: $M = 18.3$ h, SD = 3.88). Autistic participants primarily attended autism social community network groups for social interactions.

To measure autistic features, participants completed the Social Responsiveness Scale—Second Edition (SRS-2; Constantino & Gruber, 2012). The SRS-2 asks participants to rate 65 statements relative to their behavior over the past 6 months by ranking the items from 1 "not true" to 4 "almost always true." The raw scores were calculated and converted to *T*-scores based on chronological age and sex norms. As expected, the autistic group obtained significantly higher SRS-2 scores ($M = 67.96$, SD = 8.93) compared to the non-autistic group ($M = 48.82$; SD = 7.3), $t(51) = 8.45$, $p < 0.001$, $d = 2.32$.

Intellectual functioning was measured using the Wechsler Abbreviated Scale of Intelligence—Second edition (WASI-II; Wechsler, 2011). Participants took part in all four subtests: Vocabulary, Similarities, Block Design, and Matrix Reasoning. To establish full-scale IQ (FSIQ-4), verbal comprehension (VCI), and perceptual reasoning (PRI) raw scores were converted to *T*-scores. An independent-samples *t*-test revealed no significant group differences for FSIQ-4, VCI, or PRI (see Table 2).

Stimuli and procedure

All participants completed a lexical decision task followed by a categorization task. The auditory stimuli had been used in prior research and were naturally produced recordings by an Australian English female monolingual speaker (Bruggeman & Cutler, 2020). The lexical decision task was made up of 40 target words, 60 filler words, and 100 nonwords. Target words were presented with both unambiguous fricatives (i.e., /f/ and /s/) in words such as /profit/ and /crusade/. Four lists were created resulting in two test conditions (Condition 1: target words contained unambiguous /f/ and ambiguous /s/ sound; Condition 2, target words contained unambiguous /s/ and ambiguous /f/ word-final sounds). Condition trials were presented in a pseudo-random order except for the initial

TABLE 3 Percentage of correct responses and response times (measured from target word onset) to experimental items in the auditory lexical-training task by non-autistic (NA) and autistic (AUT) participants

	NA	AUT	NA	AUT
Training condition	***M* % "yes"**		***M* RT "yes" (ms)**	
[f]-trained group				
Natural fricatives	98	97.7	1000.6	1136.6
Ambiguous fricatives	99	93.8	1016.4	1169.2
[s]-trained group				
Natural fricatives	96.4	93.9	1037.4	1145.2
Ambiguous fricatives	59.3	63.6	1295.7	1309.7

12 trials, which were always the same six fillers and six nonwords. No more than four words or four nonwords were presented consecutively.

Participants were tested in a quiet room. Prior to the commencement of the experiment, participants were instructed that they would hear some words and nonwords, and their task was to indicate whether each auditorily presented stimulus item was a real English word by pressing one of two keys labeled "yes" or "no." Instructions were also presented on the computer screen. There was no time limit for participants' responses; however, participants were instructed to respond as quickly and accurately as possible.

After completing the lexical decision task in the training phase, participants took part in a post-test categorization task and were presented with recordings of five steps from the English /fu/-/su/ continuum. Participants were told that they would hear a sequence of sounds and were required to categorize these as either /fu/ or /su/ by pressing the [f] or [s] keyboard buttons. The task consisted of 150 randomized test trials (30 per continuum step). Instructions were also presented on the computer screen. Both tasks were presented utilizing the computer software E-Prime 3 (Schneider et al., 2016) and sounds were played at a comfortable listening level over Sennheiser HD 280 headphones. The experiment took approximately 20 min to complete.

RESULTS

Auditory lexical-decision task

As would be expected of native speakers, the non-autistic group showed near-ceiling performance. The [f]-trained and [s]-trained participants, respectively, responded correctly to 96.8% and 96.5% of the word fillers and 86.9% and 91.4% of the nonword fillers. The [f]-trained and [s]-trained autistic participants, respectively, also showed near-ceiling performance by responding correctly to 93.8% and 94.2% of the word fillers, and 80.5% and 88.5% of the nonword fillers. For both groups, lexical decision performance for the critical experimental items broken down by training condition is summarized in Table 3.

A generalized linear mixed-effects (*glmer*) model with the logit-link function, implemented in the lme4 package (Bates et al., 2015) in R (R Core Team, 2018) was fitted. Fixed factors were training condition ([f]-bias vs. [s]-bias; deviation coded: −0.5, 0.5) pronunciation (natural vs. ambiguous; deviation coded: −0.5, 0.5), and group (autistic vs. non-autistic). A maximal random effects structure was used (Barr et al., 2013), with random intercepts for participant group and items, as well as random slopes for pronunciation by groups (see Table 4).

There were significant main effects of training condition and pronunciation, an interaction between training condition and pronunciation, and, as predicted, a three-way interaction between training condition, pronunciation, and group.

To explore the three-way interaction, we analyzed lexical decision performance for the individual groups in turn. Two separate *glmer* models were fitted, using the same fixed factors (training condition ([f]-bias vs. [s]-bias; deviation coded: −0.5, 0.5) and pronunciation (natural vs. ambiguous; deviation coded: −0.5, 0.5)), and random intercepts for participants and items, as well as random slopes for pronunciation by participant for each fit. Results are displayed in Table 5.

For the non-autistic group, a significant interaction between training condition and pronunciation indicated that [s]-trained listeners accepted a greater number of natural fricatives as real words than ambiguous fricatives; this difference was not observed for [f]-trained listeners. This pattern of results suggests that the non-autistic group judged the ambiguous fricative to be acceptable instances of English [f] or [s], although it was less consistently accepted as [s].

For the autistic group (Table 6), there were significant main effects of training condition and pronunciation, but no significant interaction. The autistic group consistently judged the ambiguous fricative to be acceptable instances of English [f] or [s], although, like the non-autistic group, it was less consistently accepted as [s]. For both groups, lexical decision scores during this training phase are sufficient to observe lexically-guided perceptual learning in the phonetic categorization post-test.

Post-test: Categorization

To first determine overall learning effects between listeners, a "learning-consistent" category was created for each group (as per Scharenborg et al., 2015). This was done by combining the [f] responses made during the phonetic categorization task by the [f]-trained group with the [s] responses made by the [s]-trained group. To achieve this, percentages of items categorized as /f/ or /s/

TABLE 4 Fixed-effect estimates of grouped listeners' accuracy in the auditory lexical-training task

Fixed effect	*β*	SE	*z*	*p*
Intercept	−3.934	0.367	−10.718	<0.001*
Training condition	3.2558	0.563	5.783	<0.001*
Pronunciation	1.4865	0.491	3.027	0.002*
Group	0.5907	0.570	1.0394	0.30
Training condition:Pronunciation	3.6108	1.039	3.474	<0.001*
Training condition:Group	−0.8485	1.048	−0.810	0.42
Pronunciation:Group	0.7898	0.809	0.976	0.33
Training condition:Pronunciation:Group	−3.3206	1.6764	−1.981	0.048*

Note: Significant differences ($p < 0.05$) are marked with an asterisk (*).

TABLE 5 Fixed-effect estimates of non-autistic (NA) listeners' accuracy in the auditory lexical-training task

Fixed effect	*β*	SE	*z*	*p*
Intercept	−4.204	0.491	−8.57	<0.001*
Training condition	3.422	0.754	4.536	<0.001*
Pronunciation	1.547	0.768	2.014	0.044*
Training condition:Pronunciation	4.955	1.454	3.407	<0.001*

Note: Significant differences ($p < 0.05$) are marked with an asterisk (*).

TABLE 6 Fixed-effect estimates of autistic (AUT) listeners' accuracy in the auditory lexical-training task

Fixed effect	*β*	SE	*z*	*p*
Intercept	−3.64	0.496	−7.343	<0.001*
Training condition	2.833	0.786	3.669	<0.001*
Pronunciation	1.602	0.621	2.58	0.005*
Training condition:Pronunciation	2.49	1.37	1.817	0.07

Note: Significant differences ($p < 0.05$) are marked with an asterisk (*).

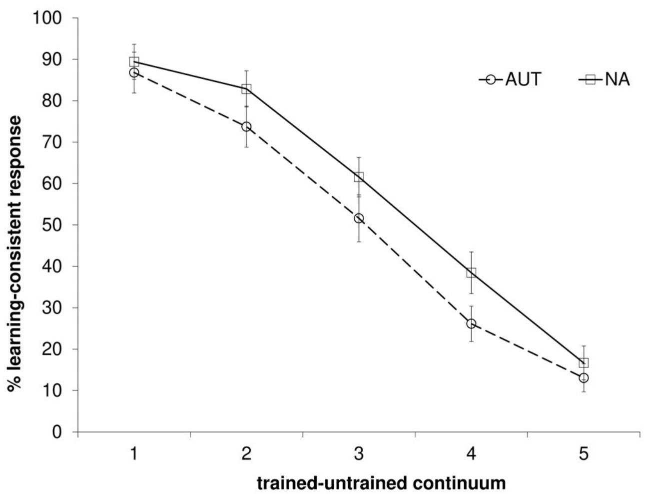

FIGURE 1 Learning-consistent categorization responses (%) made by the non-autistic (NA) and autistic (AUT) listeners along with the five continuum steps

during the categorization task were calculated for each group and for each continuum step (coded as 0 and 1 for *not learning* and *learning*, respectively).

Inspection of Figure 1 suggests that the non-autistic participants made more learning-consistent responses than the autistic participants during the phonetic categorization task. In line with previous literature (Scharenborg et al., 2015), to examine potential group differences, we analyzed data from the most ambiguous stimulus steps, namely Steps 2, 3, and 4. A generalized linear mixed-effect model (Baayen, Davidson, & Bates, 2008), with family "binomial" and the logit-link function was fitted, with deviation coded fixed factors: Step Continuous, centered on Step 5 (Step 2 as −1, Step 3 as 0, Step 4 as 1); and Group (autistic coded as −0.5 and non-autistic as 0.5). There were no significance effects of stimulus step or interaction between stimulus step and group. There was, however, a main effect of group ($p = 0.02$), indicating learning-consistent differences between groups (see Table 7).

To further determine whether perceptual learning occurred in the non-autistic participants, and between the [f]- and [s]-trained conditions, a *glmer* model with family "binomial" and the logit-link function was fitted. Deviation coded fixed factors were continuum step, which was centered on Step 3 (Step 1 coded as −2, Step 2 as −1,

TABLE 7 Fixed-effect estimates of learning-consistent results between groups across the [fu]-[su] continuum

Fixed effect	β	SE	z	p
Intercept	0.287	0.152	1.892	0.058
Steps continuous	−0.084	0.090	−0.932	0.352
Group	−0.716	0.303	−2.364	0.02*
Steps continuous:Group	−0.007	0.180	−0.041	0.967

Step 3 as 0, Step 4 as 1, and Step 5 as 2); and training condition ([f]-trained coded as −0.5, [s]-trained as 0.5). Random intercepts were added for participants and items, and random slopes for continuum step by participant, and for training condition by item (see Table 8).

The model revealed that for non-autistic participants there was a significant main effect of the continuum step. Importantly, a significant main effect of training condition provided clear evidence of perceptual learning.

To explore categorization responses for autistic listeners, a second *glmer* model was fitted using the same fixed metrics and random structure as for the non-autistic group. Results of this model fit are displayed in Table 9. Although both listener groups exhibited similar lexical decision patterns, categorization results showed no significant effects other than the continuum step for autistic listeners. As predicted, these results indicate that perceptual learning was observed only in the non-autistic group (see separation of lines for [f] vs. [s]-trained non-autistic listeners but overlapping lines for autistic listeners in Figure 2).

DISCUSSION

The present study sought to determine whether autistic adult listeners show phonetic perceptual adaptability and flexibility when attending to speech from a previously unencountered talker using a classical perceptual learning paradigm. The results of the non-autistic group are in line with previous findings that exposure to only a few instances of an ambiguous phoneme is sufficient to elicit lexically-guided perceptual learning (Cutler et al., 2018; Drozdova et al., 2016; Kraljic & Samuel, 2006; McQueen et al., 2006, 2012). While autistic adults were able to successfully discern lexical items and categorize speech sounds, they did not show evidence of phoneme adaptation evoked by lexically-guided perceptual learning. As predicted, the present findings contribute to theoretical accounts proposing atypicalities in flexible perceptual processing involving high-level/complex social stimuli by autistic people (Pellicano & Burr, 2012; Sinha et al., 2014; van Boxtel & Lu, 2013; van de Cruys et al., 2014).

Research has shown that lexically-guided perceptual learning facilitates rapid adaptation to the speech of novel interlocutors helping to resolve ambiguity and idiosyncratic pronunciations, allowing for effective communication. Our findings demonstrate that autistic adults distinguish effectively between real words and nonwords, and correctly identify real words when marked by an ambiguous fricative produced by an unfamiliar talker. They also show categorization acuity in their perception of the English /f/-/s/ speech sound continuum, and display categorization curves similar to non-autistic listeners. Strikingly, however, lexically-induced category learning effects were only observed in the non-autistic group, suggesting that automatic phonological retuning of prior phonemic knowledge may be unavailable in autism.

A plausible explanation for the lack of perceptual learning in the autistic group is their limited interaction with novel interlocutors. Person-to-person interactions are critical for language learning and brain development in early childhood (Kuhl, 2007), and may explain why autistic individuals often exhibit language and social cognition difficulties (Kuhl, 2010). A reduced number of novel interlocutors has even been shown to diminish perceptual flexibility in the neurotypical population. Bruggeman and Cutler (2020) found that highly proficient Dutch-English bilinguals living in Australia for almost two decades showed perceptual learning adaptation only in their second language, English. The reasons for this striking result were attributed to the fact that while being proficient and regular users of both languages, they only used English with a supply of novel talkers. That is, participants used Dutch solely when conversing with known family members, whereas English was used in and for all other social situations. Similar findings were observed for Mandarin-English early bilinguals (Cutler et al., 2018), leading to the proposal that adaptation to novel interlocutors is a language-specific skill requiring *regular* practice. Engaging with a limited set of known talkers does not meet this requirement and may lead to category adaptation dormancy (Bruggeman & Cutler, 2020).

The participant groups of the current study only differed significantly across three domains, namely age, SRS-2 scores and hours spent interacting with others outside of their immediate circle of family and friends (Table 1). Given that perceptual learning outcomes in this context are not influenced by age and that there were no group differences in overall IQ scores, perceptual inflexibility in the autistic group may, therefore, be a by-product of a reduction in social and communicative diversity. Here, non-autistic listeners reported spending an average of 18.25 h per week interacting with interlocutors outside of their known circle of family and friends, compared to 2.72 h in the autistic group. Autistic listeners' perceptual system may therefore benefit from higher exposure to speech of novel talkers, which could in turn result in increased perceptual flexibility through experience (Samuel & Kraljic, 2009).

Although our autistic adults show the ability to effectively process complex speech, retuning to already existing categories does not occur in the same manner as in

TABLE 8 Fixed-effect estimates of categorization scores by neurotypical listeners at post-test of the five selected steps from the [fu]-[su] continuum

Fixed effect	*β*	SE	*z*	*p*
Intercept	−0.67	0.205	−3.272	0.001
Continuum step	−1.31	0.121	−10.808	<0.001
Training condition	1.094	0.412	2.653	0.008
Continuum step:Training condition	−0.178	0.244	−0.731	0.465

TABLE 9 Fixed-effect estimates of categorization scores by autistic listeners at post-test of the five selected steps from the [fu]-[su] continuum

Fixed effect	*β*	SE	*z*	*p*
Intercept	−0.255	0.267	−0.954	0.340
Continuum step	−1.253	0.105	−11.926	< 0.001
Training condition	0.391	0.532	0.736	0.462
Continuum step:Training condition	−0.015	0.207	−0.074	0.941

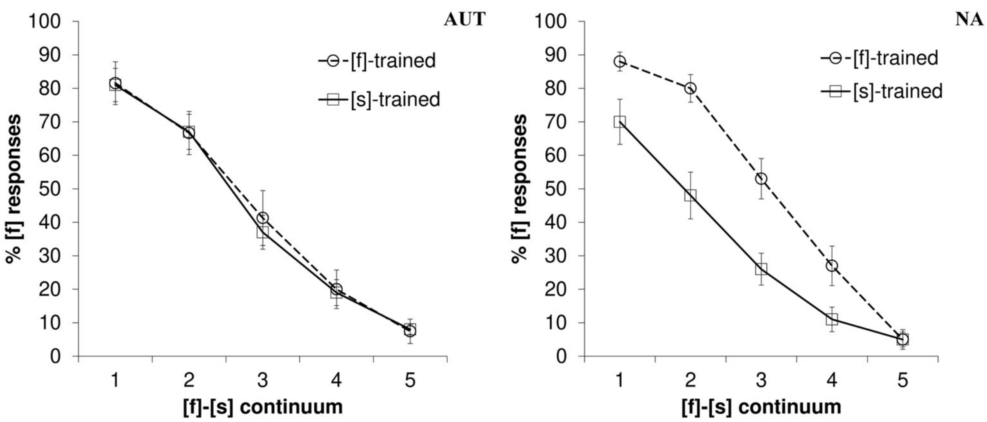

FIGURE 2 Percentage of [f] responses by autistic and non-autistic listeners along the five [f]-[s] continuum steps. Error bars show standard error of the mean

non-autistic adults. At present, only a limited number of behavioral studies have investigated the effects of lexical processing on phonemic processing in autistic people. Reports of a phonetic processing style that is less likely to be influenced by lexical information has been observed (e.g., Stewart & Ota, 2008). However, listeners reported in that study were not formally diagnosed as autistic, nor was perceptual learning explicitly investigated. Rather, it was established that lexical influence on phonemic decision-making differed for adult listeners with elevated autistic traits. Findings established in the present study are distinct in that they exhibit little evidence of lexically-guided perceptual learning in autistic listeners. Their phonological perceptual system functions as expected, but the option of adapting it to adjust to a particular talker is absent.

Perceptual atypicalities reported in visual domains may therefore also be observed in the auditory domain and even be further exacerbated in tasks where consistent attention orienting, calibration, and multisensory incorporation are required, such as speech processing involving novel talkers or idiosyncratic speech (Baum et al., 2015). Evidence links a decrease in multisensory temporal perception of social information to differentiating audiovisual perceptual abilities (e.g., De Niear, Stevenson, & Wallace, 2017), and atypical perceptual generalizations that result in perceptual inflexibility (e.g., Church et al., 2015). The complexity of the incoming speech stimuli may exceed the available auditory working-memory resources, and may further influence lower-level automatic processing and adaptation (i.e., collapsing information across multiple modalities), consequently affecting the retuning of existing phoneme categories (Ludlow et al., 2014; Marco et al., 2011). Studies suggest that this is due to speech processing requiring additional higher-level auditory integration and cortical activation (Herringshaw et al., 2016; Hixon et al., 2018).

Phonemes are often described as being organized around category exemplars that have similar acoustic attributes (i.e., prototypes), embedded in long-term memory (Khul, 1991; Nosofsky 1991). To date, it is still unclear exactly how the phonological systems of autistic people are formed (and/or retuned), whether they are marked by a limited number of prototypes, or whether atypicalities stem from underlying sensory-processing mechanisms unique to the autistic perceptual endophenotype. In autistic people, atypical perceptual organization of phonemic prototypes (Wang et al., 2017; Yu et al., 2015) and altered processing of voice and speech sounds have previously been contributed to variances in phonological acquisition patterns (Boucher & Anns, 2018) resulting in altered neural plasticity and, in consequence, reduction of phonetic flexibility (Kissine et al., 2021), of categorical precision (You et al., 2017) and of specialization for native speech sound categories (DePape et al., 2012; Stewart et al., 2018).

Weakened incorporation of lower-level with higher-level processing in the autistic group may therefore be explained by atypicalities in flexible perceptual processing set out within the Bayesian framework (Pellicano & Burr, 2012). That is, lower reliance on prior knowledge and difficulties extracting variability when processing higher-level socially relevant stimuli would result in attenuated perceptual flexibility and weakened perceptual prototypes (i.e., anomalous category formations; Pellicano & Burr, 2012). Perceptual performance may further be impeded in situations involving higher-level social stimuli affecting learning outcomes in situations where priors should help resolve ambiguity (Pellicano & Burr, 2012). A decreased ability for rapid calibration involving higher-level cognitive demand tasks such as lexically-guided perceptual learning would therefore result in skewed adaptation plasticity at the lower prelexical level, as is consistent with the current results.

Given that our autistic listeners' phonological retuning of existing phoneme categories appears to be atypical, alternate explanations for the lack of lexically-guided perceptual learning may also link to earlier accounts of differentiating neural pathways being activated when attending to speech. Atypical lateralization of both structure and function during auditory language processing has been reported across numerous neuroimaging modalities (e.g., Finch et al., 2017; Gervais et al., 2004; Herringshaw et al., 2016). Anomalous lateralization appears to be specific to temporal language networks, and has not been observed to occur-in other networks such as the Theory of Mind network or Multiple Demand network (Dufour et al., 2013; Jouravlev et al., 2020; Nielsen et al., 2014). Asymmetric lateralization suggests a possible lack of language specialization (Redcay & Courchesne, 2008), reducing efficient perception and production of language (Boddaert et al., 2003, 2004). Varying neural and asymmetric speech integration processes would therefore result in different adaptation processes required between the interaction of higher-level lexical processing and lower-level retuning of phonetic categories (Herringshaw et al., 2016; Hixon et al., 2018; Stevenson et al., 2018), and account for differences between our two participant groups. Due to insufficient spatial resolution, neuroimaging studies have as yet not ascertained what exactly takes place with phoneme categories during lexically-guided perceptual learning, in neurotypical populations or otherwise (Scharenborg et al., 2018; Yi et al., 2019). Further neuroimaging studies are needed to investigate neural pathways involved in phonemic category adaptation, as well as their formation, across varying developmental trajectories in the autistic population.

Limited evidence exists to indicate gender differences in high-level and/or complex speech-sound processing in both the neurotypical (Sato, 2020) and autistic populations (Rosenblau et al., 2017). Nevertheless, future investigations are required to identify whether the present findings are indicative of perceptual learning patterns within particular autistic subgroups or whether these perceptual mechanisms are a distinct processing marker within the broader autistic population. For instance, emerging evidence suggests that women are often diagnosed in late adolescence or adulthood (Hull et al., 2020), and exhibit gender-specific camouflage and social adaptation behaviors (Kerr-Gaffney et al., 2021; Livingston & Happé, 2017). Note that these behaviors would not affect the automatic speech processing investigated in our study, especially given that participants are required to listen to audio rather than interact with their interlocutor in person. However, it would be interesting to further investigate gender-specific speech processing in early-compared to late-diagnosed individuals. While scores obtained through our SRS-2 screening further suggest that social difficulties in the daily lives of our non-autistic group are not experienced in the same manner compared to the autistic group, future studies should endeavor to investigate whether the present perceptual patterns also transpire in real-time in person interactions.

Additionally, higher exposure to stimuli and training of voice could be investigated. For instance, consider the empirical accounts that autistic children utilize repetitive sequences of speech (i.e., echolalia) when their model is produced by interlocutors, but do not repeat their own speech in this way. This may suggest that such sequences serve as a communicative and learning tool for processing and attaining structural language properties (Kissine et al., 2021), rather than being a nonfunctional indicator of autism (Van Santen et al., 2013). Such a compensatory strategy could, of course, be facilitated in adulthood and may further suggest that phoneme category adjustment may be achieved over a longer period of time in autistic people. Such findings would aid in characterizing auditory processing patterns by autistic people and may contribute to more tailored interventions in relation to speech and language perception.

In sum, perceptual learning for talkers depends at least in part on phonological flexibility and the ability of neural networks to adjust based on listening experience. Given the substantial evidence produced in the literature to date that autistic listeners show atypical processing of voice and speech sounds, as well as less flexibility in social interaction, the present study sought to examine auditory perceptual learning effects in such listeners. Our results revealed that autistic listeners have an apparently unimpaired ability to use their existing lexical knowledge, but are limited in the flexibility required to update speaker-specific phonemic knowledge when exposed to a novel talker.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Western Sydney University at https://doi.org/10.26183/K6B0-YD10.

ETHICS STATEMENT

This research has been approved by the Western Sydney University Human Research Ethics Committee.

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