Sex and age independent predictive call sequence alterations of pups in an autism spectrum disorder mouse model

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Abstract

Social communication deficit is a hallmark of autism spectrum disorders (ASDs). Mouse ultrasonic-vocalizations (USVs), with communicative significance, are extensively used to probe vocalization-based social communication impairment. However, most studies on ASDs mouse-models show inconsistent alterations in USVs based phenotypes over age and sex. Despite the predictable nature of mouse USVs, very few studies have taken advantage of the same. The current work explores USV pup-isolation-call (PIC) features and alterations in structural content of predictive PIC sequences of the well-established *in-utero* valproic-acid (VPA) exposure-based ASDs model. Our study shows the importance of higher-order USV structures, with speech-like sequential dependencies that have consistent alterations in ASDs model at all developmental ages and sex. In addition to confirming prior observations of reduced call rates and durations, as well as heightened peak frequencies in ASD model pups, our data underscores inconsistent trends in the call features across sex and age. The varying nature of call features in ASD models poses a substantial challenge in assessing intervention outcomes. The above inconsistency complicates the differentiation between the effects of aging and therapeutic impacts. Establishing consistent alteration in USVs could help uncover age- and sex-independent changes in ASD models, shedding light on associated therapeutics and developmental mechanisms.

Keywords: Autism Spectrum Disorder (ASDs), Valproic acid (VPA), Ultrasonic Vocalization Sequences (USVs), mutual information(MI), informative sequences

Introduction

Autism Spectrum Disorder (ASDs) are a neurodevelopmental disorder characterized by various deficits, one of the common and earliest symptoms of which is the impairment in speech development[1]. Mouse USVs and human speech both involve vocalizations that are of communicative significance, but they have distinct characteristics and complexity levels, making them difficult to compare[2]. Nevertheless, at the rudimentary level, any alterations in the structure of the USVs emitted could serve as readout of communicative deficits in laboratory conditions. Thus, pup USVs emitted have been utilized to identify ASDs-like behaviors, which are not easily measurable with other behavioral indices during early developmental age [3,4].

Among the various ASD models, *in-utero* exposure to VPA is well-established[5,6,7,8]. A resemblance in behavioral deficits has been observed in prenatally VPA-exposed rodents as in human offsprings[9]. Since then, various studies have explored the pathways linked with ASDs-like behavioral impairments using the VPA model, which has a similarity in the underlying cause and the spectrum of human ASD phenotypes[9,10]. Some studies previously characterized autistic-like phenotypes in VPA mouse models with either a bias for male offspring[11,12,13,14] or not focusing on sex specificity [15,16,17] while others have explored the same in a sex-specific way[18,19,20]. However, none of the studies have focused on alteration in USVs as a phenotype that is consistent for both sex over age. By focusing on features that are affected independent of sex, we can avoid overlooking autism in females and ensure that all individuals with autism, regardless of sex, receive timely and appropriate support.

Our work focuses on the differences between typically developing (TD) and VPA pups over developmental age, considering the USV acoustic features, the composition of syllables, and also leveraging the predictiveness and presence of structure well known in mice by tracking high-order informative sequences[21,22]. Our results align with the previous studies in terms of a general reduction in call rate, elevated peak frequency, and shorter call duration for ASD pups, which are inconsistent over developmental age. However, at the level of higher-order structures, the anomalies were prominent in VPA pups independent of sex and age. Thus, our study opens avenues to utilize structural analyses of neonatal vocalizations to assess early socio-communicative deficits in ASD models independent of sex and age.

Results

To elucidate the differences in VPA mouse models compared to typically developing ones for both male and female pups, we started our investigation by looking first at the basic acoustic features of the syllables, namely call rate, syllable duration, and mean peak frequency. In Fig. 1A, the steps involved in the generation of the VPA model till the recording of pup vocalizations are depicted. The pups were isolated from their mother and their vocalizations were recorded for 5 min (see Methods and Materials for details). In Fig. 1B-E, four example spectrograms of each syllable type are shown. Call rate, syllable duration and mean peak frequency were quantified for acoustic features. Repeated measure(RM) ANOVA was performed to assess the effect of treatment(TD or VPA)x Sex x Age. Subsequently, post hoc analysis was performed with Tukey's multiple comparison test. The sample size used in the study containing the number of animals, litters, syllables and bouts are tabulated in Table 1.

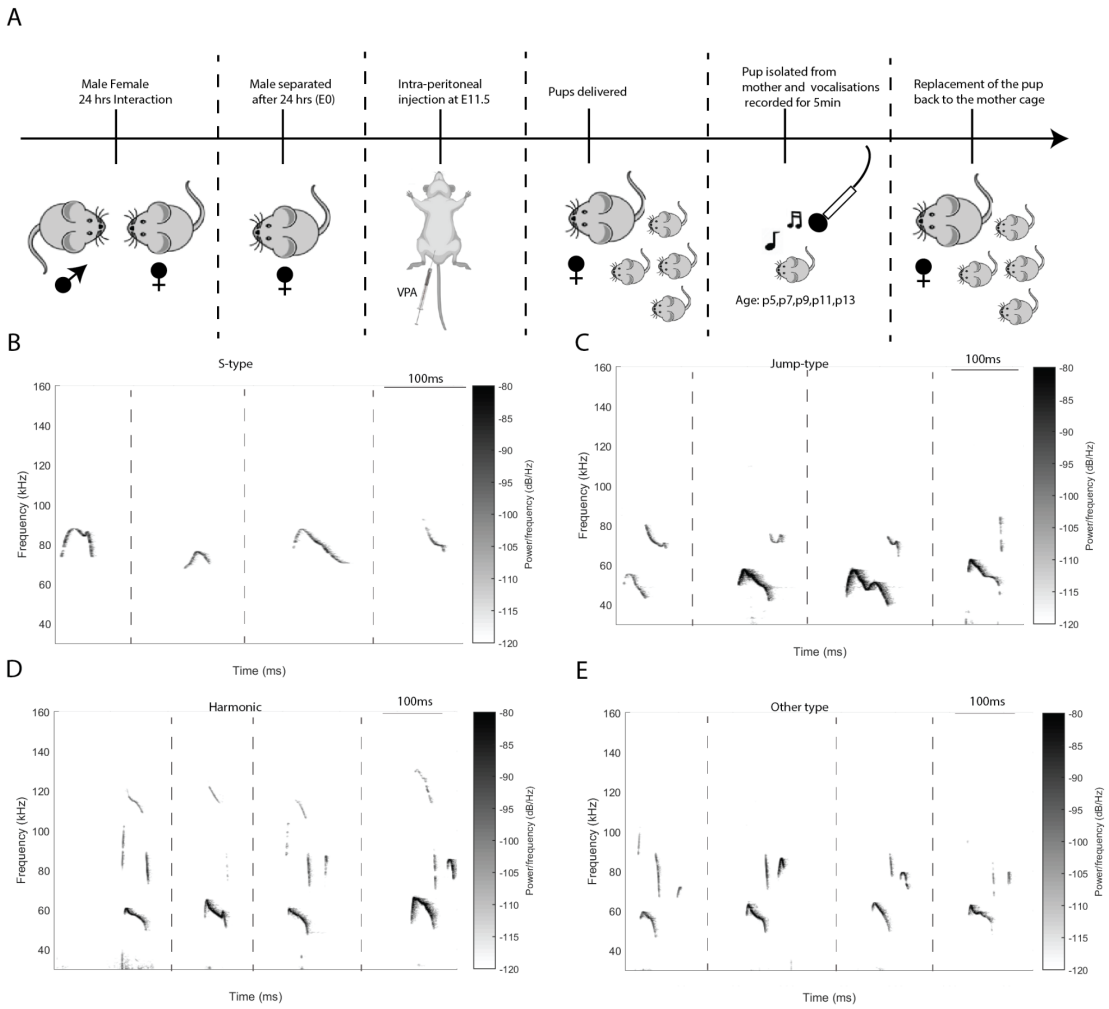

Figure 1: A) Schematic of the generation of the VPA model and recording of pup-isolation-calls(PICs). Representative spectrogram of syllables types B) S-type C) Jump-type D) Harmonic E) Other types. Four examples are shown for each of the syllable types (A-E). Dashed vertical lines show different examples of a syllable category. Scale bar shown on the top right of each figure.

TDMp(n=8, 3 liters)	#syllables	#bouts	TDFp(n=7, 3 liters)	#syllables	#bouts
p5	2443	494	p5	2146	418
p7	3252	713	p7	3757	754
p9	1929	499	p9	2251	643
p11	1270	379	p11	2197	606
p13	1254	401	p13	884	386
VPAMp(n=6, 3 liters)	**#syllables**	**#bouts**	**VPAFp(n=6, 3 liters)**	**#syllables**	**#bouts**
p5	1957	443	p5	1845	400
p7	1319	363	p7	1237	373
p9	979	506	p9	1894	679
p11	1253	412	p11	1787	346
p13	435	161	p13	772	307

Table 1: Sample size used for the current study. The table includes numbers of animals(n), litters from different parents, syllables and bouts for different age groups in TD and VPA for male and female offsprings. Notably each litter had a minimum of 2 pups.

Call rate: The average number of calls emitted by pups per minute is shown in Fig. 2. Independent of age and sex, the average call rate was lower for VPA compared to TD. A RM ANOVA followed by a post-hoc analysis by Tukey multiple comparison considering the age as the within group variable revealed that VPAMp exhibited significantly less calls than TDMp at p7($p<0.001$) and p9($p<0.05$) as shown in Fig. 2A and for VPAFp at p7($p<0.001$), p9($p<0.05$) and p11($p<0.01$) as in Fig. 2B. No sex specific differences were observed between the TDMp and TDFp.

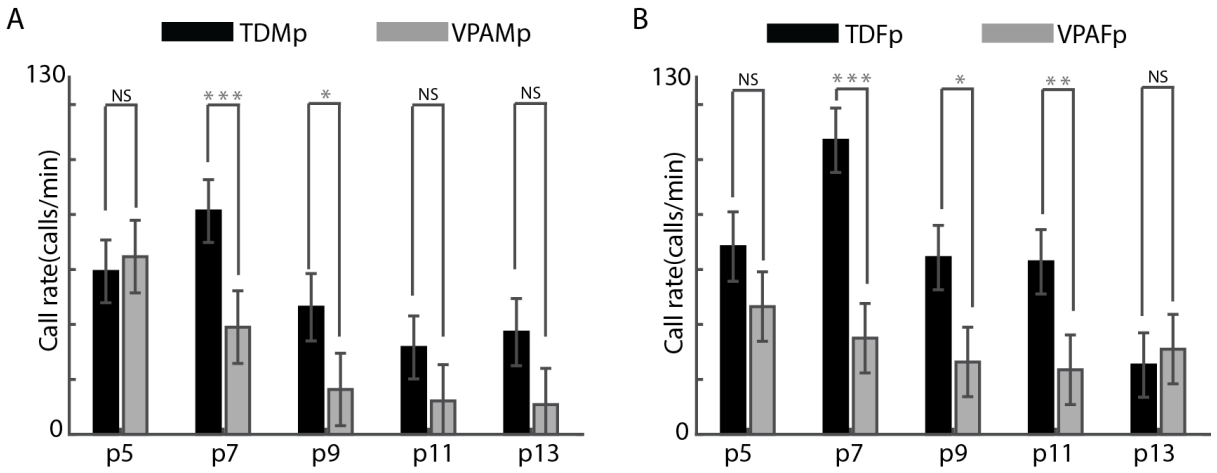

Figure 2: Comparative study of the call rate (calls per minute) in typically developing TD (black) and VPA (gray) pups in A) TDMp versus VPAMp B) TDFp versus VPAFp. RM ANOVA with Post-hoc analysis by Tukey multiple comparisons *p<0.05,p<0.01,***p<0.001, NS-non significant.**

Syllable duration: The mean syllable duration for typically developing male (TDMp, black) and VPA male (VPAMp, gray) pups is shown in Fig.3A, and similarly for typically developing female (TDFp, black) and VPA female (VPAFp) pups Fig.3B. On average, VPA pups have a shorter syllable duration compared to the TD. A RM ANOVA reveals a significant effect of age on mean syllable duration. Also there is a significant interaction between group types i.e; VPA or TD with age. Post-hoc analysis by Tukey multiple comparisons revealed a significant difference in syllable duration between TD and VPA male at p5(p<0.001), p7(p<0.05) and p9(p<0.01) but not in female(except at p7(p<0.001)). No sex-specific difference was observed between the TD male and female group.

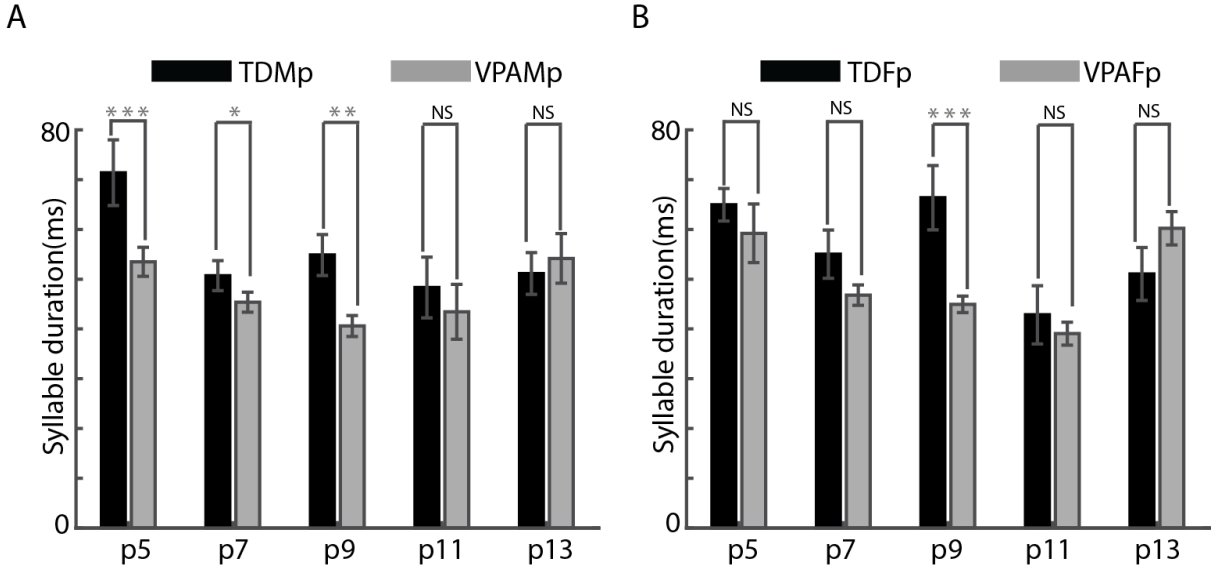

Figure 3: Comparative analysis of syllable duration over developmental age
Comparative study of the syllable duration in A) TDMp (black) versus VPAMp (gray) B) TDFp (black) versus VPAFp(gray). RM ANOVA with Post-hoc analysis by Tukey multiple comparisons *p<0.05,p<0.01,***p<0.001, NS-non significant.**

Mean peak frequency: The mean peak frequency is shown for male TD (TDMp, black) and VPA (VPAMp, gray) pups on the left side of Fig. 4 and similarly for female TD (TDFp, black) and VPA female (VPAFp) pups on the right side). Independent of sex and age, VPA pups on average have a higher mean peak frequency than the TD. A RM ANOVA reveals no significant effect of age on mean peak frequency. Also there is no significant interaction between group types i.e; VPA or TD with age. Post-hoc analysis by Tukey multiple comparisons revealed a significant difference between TD and VPA male at each age (Fig.4A) which was absent in female(Fig.4B) at all ages. No sex-specific difference was observed between TDMp and TDFp .

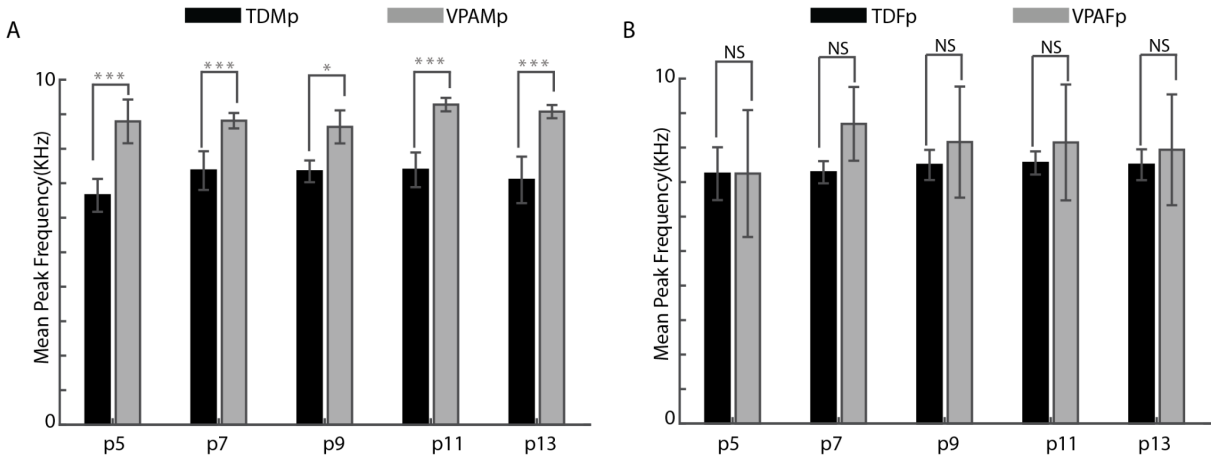

Figure 4: Comparative analysis of mean peak frequency over developmental age
Comparative study of the mean peak frequency in A) male pups TD (TDMp,black) versus VPAMp(gray). B) female pups TD (TDFp,black) versus VPAFp(gray). RM ANOVA with Post-hoc analysis by Tukey multiple comparisons *p<0.05,p<0.01,***p<0.001, NS-non significant.**

Probability mass function (PMF) of syllables

In the current study, the syllables were categorized into four types based on the spectro-temporal features[21,22], as shown in Fig. 1B-E. To investigate further if there is a consistent alteration independent of sex and age, we looked at the proportion of each syllable type for both VPA male and female pups and compared them to their respective typically developing (TD) groups.

The proportion of syllables for TDMp and VPAMp is shown in Fig. 5A, left top, and TDFp and VPAFp in Fig. 5C, right top. Each row of the matrix represents the different age groups, and each column corresponds to different syllable types. For both TDMp and VPAMp, S-type syllables are dominant in proportion over age. Further, to understand how the distribution of the proportion of syllable type changes within a group with age, we first measured the Kullback Leibler Divergence (KLD) (see Methods and Materials for details) in bits for each group TD and VPA. In Fig. 5B, the first column of the matrix depicted by an arrow represents how distant the distribution of the proportion of syllable types at the age of p5 are from p7(first row), p9(second row), and so on. Between any two age groups, the distance can be observed from the diagonal matrix by comparing the corresponding columns and rows of that age. In TDMp (Fig. 5B, left), the disparity in distribution diminishes with age, illustrated by the final row indicating the distance from each age to p13. The white asterisk highlights significant differences at a 95% confidence interval. Notably, there are significant discrepancies between each age in TDMp. Conversely, in VPAMp (Fig. 5B, right), the distribution appears more consistent across ages compared to TDMp. Noteworthy is the absence of a significant difference between p7 and p9, and between p5 and p13, a smaller distance between ages compared to TDMp. A similar analysis was done for typically developing female pups (TDFp) and VPAFp, as shown in Fig.5D. S-type syllables are the dominant ones in female pups, too, as observed in male pups. In Figure 5D, the consistency in distribution across ages is more uniform in TDFp (Fig. 5D, left) than in VPAFp (Fig. 5D, right). Thus, unlike VPAMp, VPAFp has more variability in the proportion of syllable types emitted over developmental ages.

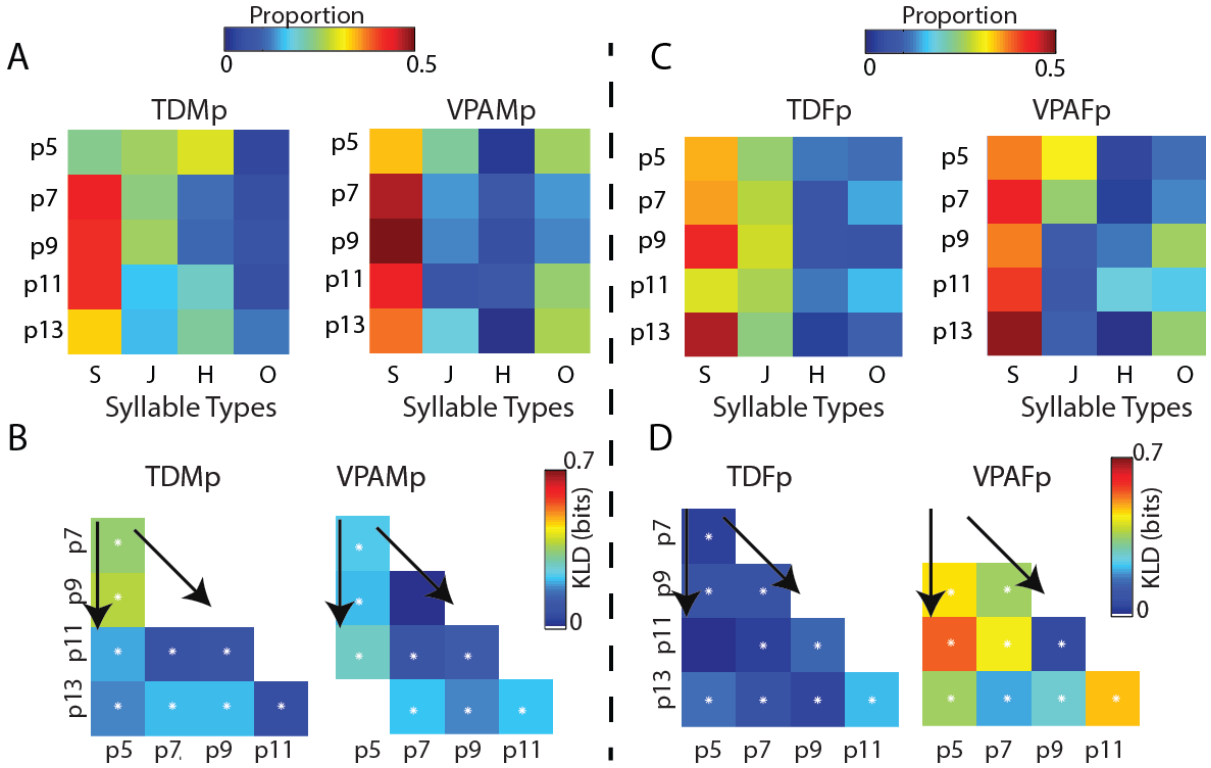

Figure 5: Frequency of occurrence of syllables over developmental age
A) typically developing male pups (TDMp, top left) and VPAMp(bottom, left). B) KLD among the distributions of typically developing male pups (TDMp, top left) and VPAMp(bottom, right) C) typically developing female pups (TDFp, top left) and VPAFp(bottom, left). D) KLD among the distributions of typically developing female pups (TDFp, top left) and VPAFp(bottom, right) . White asterisk indicates significant KLD at 95% CI.

Transition of syllables

After exploring the composition of syllables, the next step was to look at the transitions of two syllables (see Methods and Materials for details). Sequences of syllables were analyzed considering two successive syllables by considering only the starting two syllables in bouts. Syllable-to-syllable transitions were quantified using the joint probability distributions, that is, the probability of occurrence of every possible pair of syllable types. The joint distributions are shown in the form of matrices in Fig.6A (first two syllables of a bout) for TDMp (first column) and VPAMp (second column) over developmental age. For TDMp, S-S, S-J, J-J, J-S, and H-H transitions are the most prominent across all the ages except p13, where J-J and J-S are insignificant. In contrast, VPAMp has no H-H transitions and seems to change with age with no consistent pattern. Also the J-S, J-J were not significant in VPAMp after p5. The diagonal matrices in Fig.6B show the KLD among the distributions.
A similar analysis is done for syllable-to-syllable transition for females Fig. 6C. TDFp (third column) showed a consistent pattern of transitions either from S-S, S-J, J-S, and J-J across all the ages but for VPAFp (Fig. 6C, fourth column), there was much variability in the pattern with age and interestingly similar to VPAMp had H-H and J-J,J-S(except p5) transitions missing. The KLD among the distributions is shown by the diagonal matrices in Fig.6D Thus, TD groups, independent of sex, preserved a pattern that was altered in VPA pups.

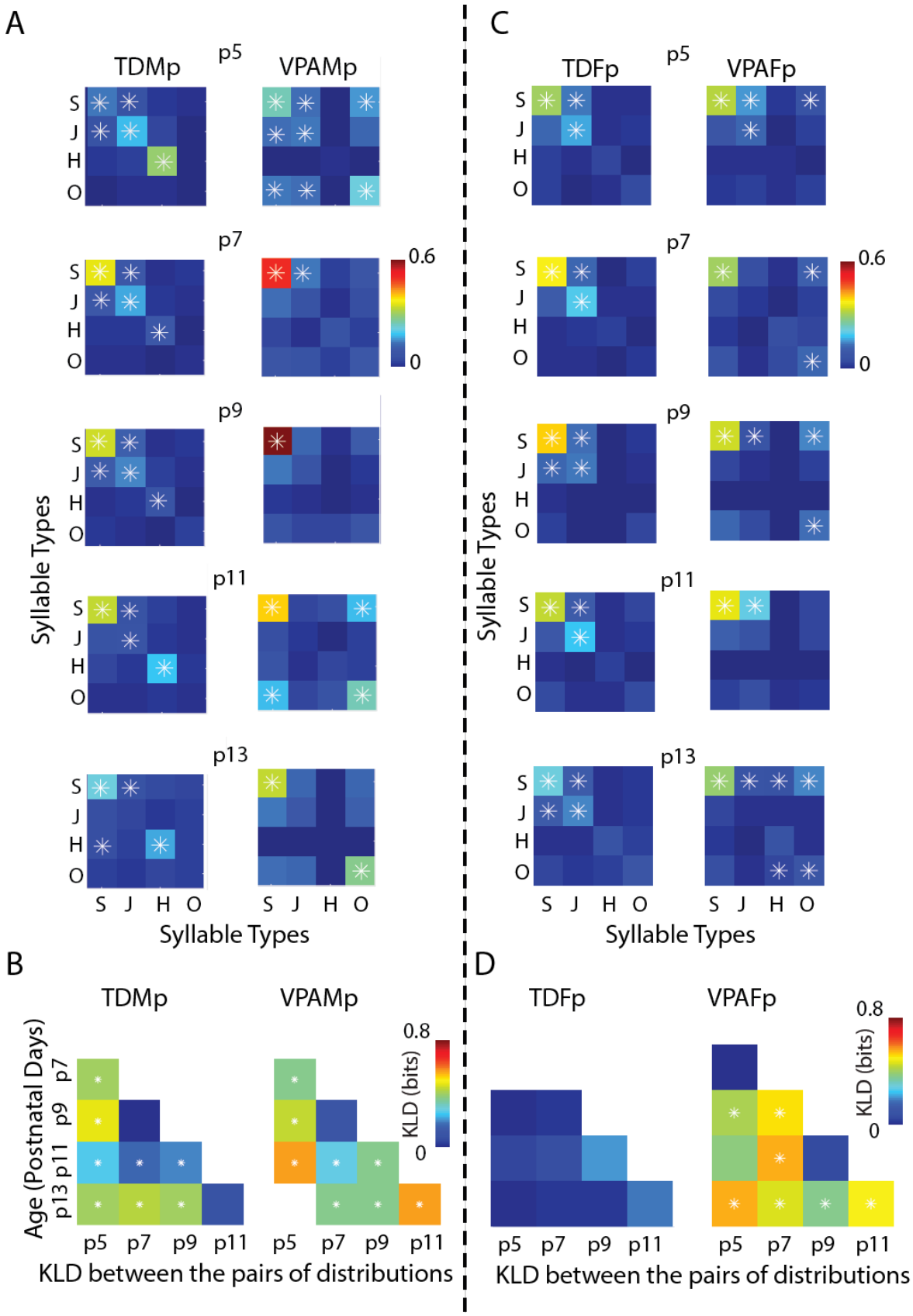

Figure 6: Syllable to syllable transition probability matrices. (A) Joint probability distributions of syllable type to syllable type transition considering starting two syllables in bouts is depicted in each of five matrices for each age p5, p7, p9, p11 and p13 for the two groups of pups, TDMp (first column) and VPAMp (second column) (Asterisks indicate significance at 95% confidence). (B) The

diagonal matrix plot quantifies the *KLD* between joint distributions for TDMp (left) and VPAMp (right). (C)Joint probability distributions of syllable type to syllable type transition considering starting two syllables in bouts is depicted in each of five matrices for each age p5, p7, p9, p11 and p13 for the two groups of pups, TDFp (first column) and VPAFp (second column) (Asterisks indicate significance at 95% confidence). (D) The diagonal matrix plot quantifies the *KLD* between joint distributions for TDFp (left) and VPAFp(right).

Comparable changes independent of sex over age at transition level but not at composition level

In Fig. 7A, we quantified the distance between the proportion of syllable types between TDMp and VPAMp within the corresponding age groups. There is a significant difference at all ages (at 95% CI) between the TDMp and VPAMp distribution of the proportion of syllables, with the highest being at p5 (solid lines). The distribution of the syllable types proportion between TDFp and VPAFp for each age is also significantly different from each other (except at p5 and p7), with the difference being highest at p9 (dashed line). In Figure 7B, the KLD between the syllable transitions is quantified. Significant difference is observed between TDMp and VPAMp for each age, with the difference highest at p5. Agewise, the transition of syllables significantly differed between TDFp and VPAFp for each age. At the composition level, as shown in Figure 7A, the difference between male and female groups is not consistent over age. However, at the transition level, except at p5, where the differences in males stand out, both the groups independent of sex exhibit comparable changes over age as shown in Figure 7B.

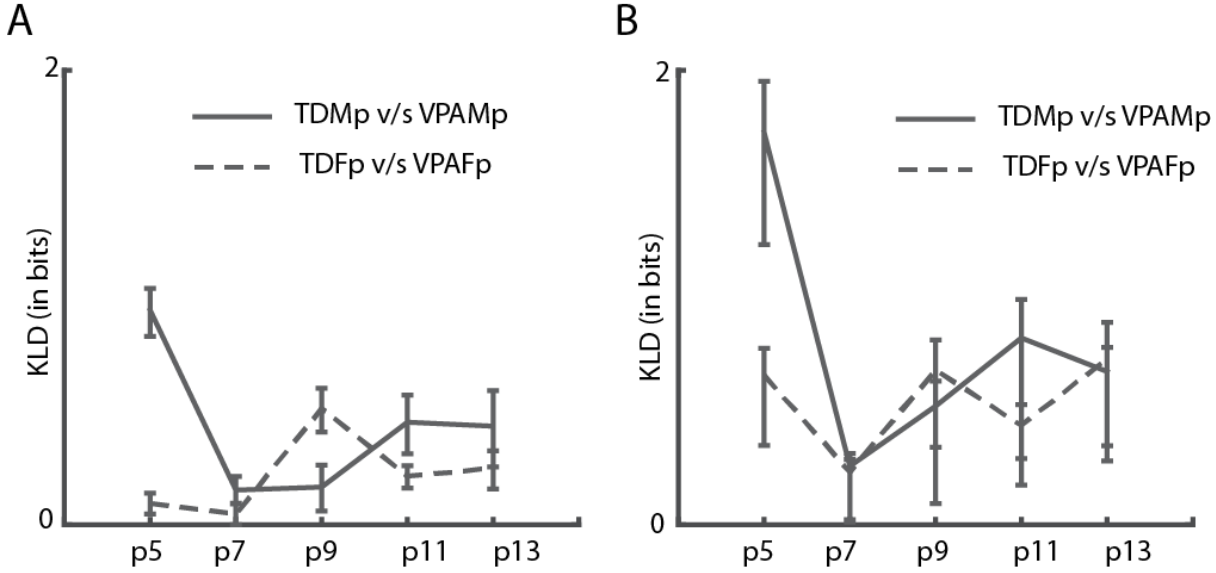

Figure 7: KLD (in bits) between A) PMF of the distributions in Figure 5 between TDMp and VPAMp (solid black lines) and between TDFp and VPAFp (dashed black lines). B) Joint distributions in Figure 6 between TDMp and VPAMp and between TDFp and VPAFp for each age.

Information theoretic measures reveal lack of structure in VPA pups independent of sex

To check for presence of higher-order structure[21,22] in the sequences of syllables first, we asked if there was any dependence between syllables. Essentially we probed to see if on average there is any order in the occurrence of the syllables or if they occur randomly. To test the above, we compute *Mutual Information(MI)* between the syllable at the start of a bout and the syllable at subsequent positions of a bout. Significant dependence or *MI* between the syllables treated as random variables would mean the presence of structure in the sequence, while lack of dependence or '0' *MI* would indicate a lack of structure. Fig. 8 and 9 show the debiased *MI* between the first syllable and the *n*th (n=2, 3, …) with

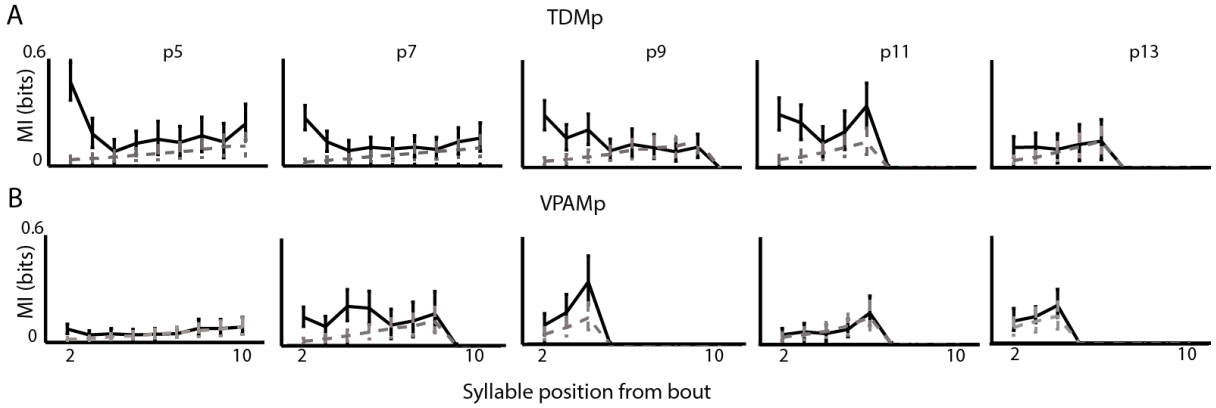

Figure 8: *MI* between the first and the *n*th syllable from the starting of a bout for male pups. The four plots show the dependence (quantified by *MI* in bits) between the first syllable and the subsequent syllables in the A) TDMp and B) VPAMp. The actual *MI* is plotted in thick black lines with error bars showing 95% confidence intervals. The dashed thin gray line shows the *MI* (with 95% confidence intervals) between the syllables at the same positions when the syllable sequences in bouts were randomly scrambled.

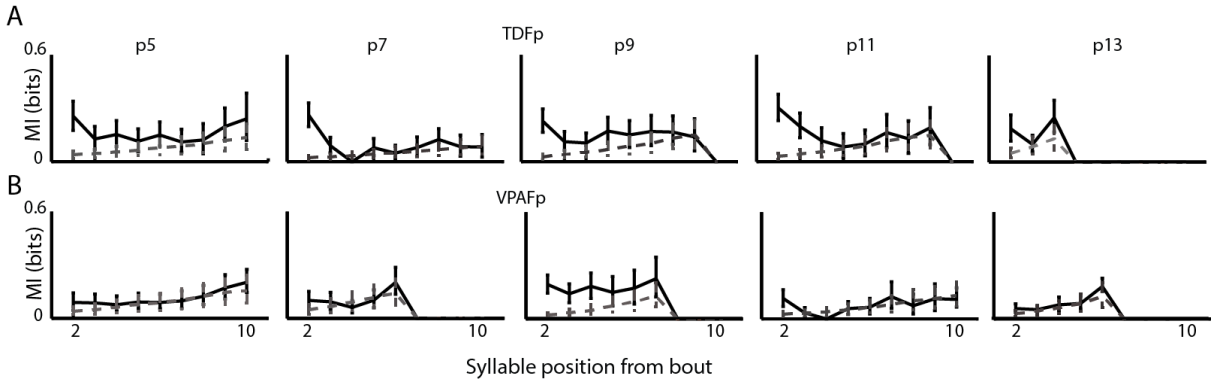

Figure 9: MI between the first and the *n*th syllable from the starting of a bout for female pups. The figure is arranged in the same way as Fig. 8, with data from female pups A) TDFp B) VPAFp.

95% confidence intervals for all the groups (solid line). The baseline is the *MI* with 95% confidence intervals for the scrambled sequences indicating the *MI* for no dependence (dashed gray line). *MI* estimates with no overlap between the two confidence intervals at each position are significant. There is a clear presence of structure in TDMp (Fig.9A, top) and TDFp (Fig.10A, top) across all ages. However, given the first syllable, the positions to which it can be predicted vary. In VPAMp (Fig. 9B, bottom) and VPAFp (Fig. 10B, bottom), we find either no or less dependency compared to TD groups. This infers that VPA pups lack predictive-ness among the syllables, which is well captured in typically developing pups over different developmental ages. We also tracked the informative sequences (see Methods and Materials section) as tabulated in Table 2. The sequences with S-S transitions were common to all the groups. The TD group of males and females also exhibited sequences with J-J and J-S transitions, which were missing in VPA pups.

	TDMp	VPAMp	TDFp	VPAFp
p5	S(4) J(4)	S(4)	S(5) J(4)	S(4)
p7	S(7) J S(2) J(2) S	S(5)	S(6) J(2) S J(3)	S(3)
p9	S(5) J(3)	S(3)	S(5) J(4)	S(4)
p11	S(4)	S(2)	S(4) J(3)	S(4)
p13	S(4)	S(2)	S(3) J(2)	S(4)

Table 2: Informative sequences in each group over developmental age

Discussion

In the current study, we leveraged the predictability and structure in the mouse USVs[21,22,23], particularly in PICs, along with acoustic features as an assay to probe ASD-like phenotypes in a VPA mouse model. We observed a general reduction in call rate, elevated mean peak frequency, and shorter call duration in VPA pups. The acoustic features, however, displayed considerable diversity across developmental ages (P5-P13) and sex, with significant differences observed at certain ages/sex while not evident at others. As an illustration, the mean peak frequency exhibited changes in VPAMp compared to the TD group across all ages. However, in VPAFp, this alteration wasn't noticeable at any age, suggesting that female pups either showed signs of recovery or were less impacted compared to males. Whereas for call rate and syllable duration at some ages for both sex significant differences were observed. However,the alteration in the VPA pups for the transition of syllables, the amount of *MI* present, and the informative sequences emitted over developmental age, were sex and age independent. Thus, taking advantage of the call structure in mouse USVs appears to be a more promising measure to interpret sex-independent abnormalities related to social communication deficits.

VPA mouse is a validated model and can serve as a valuable tool to investigate the neurobiology underlying ASD-like behavior and test novel therapeutics[5,6,7,8]. The neonatal mouse pup USVs being sensitive to social context can serve as a proxy for reduced social attachment or atypical social information processing. Thereby, various studies to date have investigated the effects on USVs emitted by the pups due to the unavailability of easily measurable behavioral indices[3,4], aiming for early detection to enable timely interventions. The USV acoustic features and the call sequences emitted undergo modulation with age in typically developing pups[23], tracking the same in the VPA pups to monitor any alterations is essential. Even though studies have targeted specific postnatal ages and sexes, pooled data across different ages/sexes, and monitored developmental changes in both sexes, a consistent pattern still remains elusive. Given the importance of consistency in comprehending the results of therapies and interventions, emphasizing the need for more reliable indicators becomes imperative. For instance, Gandal et al. 2010 observed decreased call rates in combined mouse samples across p2, p5, p8, and p12. Moldrich et al. 2013 and Cheaha et al. 2015, examined only male mice at p8 and p12, respectively, noting a decreased call rate. Kuo et al. 2017,

also focusing on male mice at p8, reported reduced call rates, and other features such as decreased duration and mean peak frequency. Melancia et al. 2018 discovered decreased call rates in p9 male rats, but females were unaffected. Tartaglione et al. 2019 considered mice of both sexes from p4 to p12; at p10, females exhibited shorter call durations, but no other postnatal days showed significant effects. Tsuji et al. 2020, studying mice of both sexes from p3 to p14, found no USV peaks in either sex and noted lower call rates in both sexes at p11. Thus, there is a discrepancy in the literature with some studies finding prominent effects at certain ages in either or both sex. In our current study, we found on average a decrease in call rate (Fig. 2), high mean peak frequency (Fig. 3), and shorter call duration (Fig. 4) for VPA pups compared to TD pups which was not consistent over ages and sex. The call rate was significantly reduced in VPAMp at p7 and p9 whereas in VPAFp, the effect was at p7,p9 and p11. Syllable duration was shorter for VPAMp at p5,p7 and p9 and for VPAFp at p7 and p9. The mean peak frequency was higher for VPAMp at all ages but not female. There seems to be a lot of variability in the basic call features based on sex and age in our current study as well as in the literature. Since no significant sex-specific difference was observed between TDMp and TDFp for call features, the data were pooled together and compared with pups obtained by prenatal exposure to saline. No significant difference was observed for call rate, syllable duration and mean peak frequency using RM ANOVA (Fig. S1). Therefore, the alterations observed in pup USVs could be linked to the exposure to VPA and not to any stress induced by the injection procedure during the pregnancy.

Alteration in the syllable composition was observed by Cheaha et al. 2015(mice), Moldrich et al. 2013 at p8(mice); Tsuiji et al., 2021(mice), p11. However, none of the studies to the best of our knowledge have looked at the composition of syllables by monitoring the within group variability as a function of age for both sex. The frequency of occurrence of syllable types (Figure 5 A,C) was altered in both VPAMp and VPAFp. Interestingly, the within-group variability in the composition of syllables was higher in VPAFp over age than in any other group (Figure 5B,D), an exciting pattern unique to VPA females. Thus, the way ASDs manifests in female mice might be different from males for a few features.

Certain studies[21,22,23] have highlighted the presence of predictability in mouse USV sequences, akin to human speech and songbirds at the rudimentary level and tracked the sequences with high predictability, named as informative sequences. The tracked sequences have been urged to carry behavioral significance beyond mere mathematical outcomes [21,22]. Agarwalla et al. 2020, reported lack of MI and altered sequences in a 16p11.2 deletion mouse model at p5 with a specificity only for male pups and not in females. The same has not been looked into for VPA pups. We thereby explored the possibility of alterations in structure and the speech-like sequential predictability[21,22] of PICs. Syllable to syllable transition probabilities form the basis of ordered structure in sequence of syllables and the MI between syllables at the first position and subsequent positions provide a degree of dependence and hence predictability in sequences. Thus, along with the above properties of sequences of PICs, as previously reported [21,22], we also tracked the informative sequences for each group[21,22]. The pattern was altered at the level of transition of syllables both for male and female VPA pups compared to TD groups (Figure 6A,C), with changes within the group over age being more for VPA females compared to typically developing female pups (TDFp), quantified using KLD (Figure 6B,D). An intriguing observation emerged: J-J(except at p5) and H-H transitions appeared to be consistently present solely within the TD group, a pattern that held true even when analyzed within individual litters. The composition and transitions in VPA females over age were more heterogeneous compared to TDFp. On quantifying the disparity between the VPA and typically developing pups at each age, we found that the KLD of the composition of syllables in males differed from p7 to p13, whereas for females, there were no significant differences at p5 and p7 (Figure 7A). Both sex had inconsistent changes over age (Figure 7A). In contrast to the above observations, at the level of transitions, the differences were comparable independent of sex (except at p5)(Figure 7B). To further investigate, the predictability present in the USV sequences was quantified using *MI* to measure the dependency of the preceding syllables on the syllable

considered to be the starting of a sequence. Typically developing pups had significant MI across all ages (except p13), whereas the VPA group lacked it (except minor dependencies at p7, VPAMp , and p9, VPAFp). We also tracked the informative sequences emitted by each group and found S-S sequences common to all. The VPA group, however, could not emit sequences with J-J or J-S transitions which were present in TD groups (Table 2). The inherent variability among pups is widely acknowledged. Our aim was to assess the extent to which this inherent variability among pups influences the sequences. We sought to understand if these sequences were resilient to variability, potentially making them a more dependable cue compared to acoustic features and syllable composition. Both TD and VPA litters exhibited S-S sequences consistently. Interestingly, the J-J or J-S sequences were consistently observed in TD pups across litters even with a loose criteria of 60 % confidence interval from p5 to p11 (p13 wasn't considered due to limited bouts within the litter). However, these sequences were absent in VPA pups when looked at litterwise. To add, although there was a variability in the presence of J-J-J across litters in TD pups across sex and age but in VPA pups, it was almost absent with a presence of maximum of 5% at p5. Thus, independent of sex, the trends observed were similar in VPA pups considering features related to the structure in USVs. Understanding sex and age-independent features in ASD research is essential for uncovering the core characteristics of the disorder, identifying biomarkers, and developing effective treatment strategies. By focusing on features that transcend sex and age differences, researchers can advance our understanding of the condition and improve outcomes for individuals with ASD.

Limitations: Although the VPA model has limitations like a generalization to the ASD population, timing and dosage of exposure might impact the results and the range of social, communicative, and cognitive impairments it mirrors as seen in humans. Still, VPA serves as a validated ASDs model for probing questions related to the epigenetic origins of ASDs due to its striking resemblance to behavioral, cellular, and molecular alterations observed in human ASDs subjects[9,10]. Experimental manipulations of the animal models can give insight into the pathways involved and the potential therapeutic targets which cannot be performed with human subjects.

Conclusion: In summary, we found that both VPA male and female pups exhibited sensitivity to alteration in call features which were inconsistent over sex and age. The composition of the syllables exhibited a similar trend as observed for call features. Interestingly, at the level of transitions, the disparity observed in VPA male pups compared to typically developing male pups was similar to that observed in VPA female pups with respect to TD female pups. Even the sequences emitted by VPA pups independent of sex were more random as the syllables lacked predictiveness between them when quantified using *MI* compared to TD pups and were altered, lacking complex transitions present in TD pups. Thus, the structure present in mouse USVs can better measure ASD phenotypes independent of sex.

Methods and Materials

All methods were carried out in accordance with relevant guidelines and regulations and all methods are reported in accordance with ARRIVE guidelines. The study design is explained by the schematic shown in Fig. 1A. The parameters assessed included call rate, mean peak frequency, call duration, frequency of occurrence of each syllable type, transition probability of syllables, MI content between the syllables in the starting and the other successive positions and tracking of informative sequences. The statistical analysis included RM ANOVA followed by post hoc Tukey multi comparison to compare TD and VPA groups over age for male and female pups. The significance of probability distributions, distance between them computed using KLD and MI content was estimated by bootstrapping and determining the 95% CI compared to the scrambled data. The vocalization recordings were

performed from pups with age group p5, p7, p9, p11 and p13 and the sex was identified. For all the results, the mean+/- sem or the distributions has been shown in the plots.

Animals

All procedures used in the study pertaining to animals were approved by the Institutional Animal Ethics Committee (IAEC) of the Indian Institute of Technology Kharagpur. C57BL6/J strain mice, *mus musculus* (age and sex identified in individual cases) used in the study were reared under a 12/12 h light/dark cycle at a temperature of 22–25°C with *ad libitum* access to food and water. Vocalization recordings were performed on a total of 17 pups, comprising 8 males and 7 females, originating from three distinct sets of parents. Each litter contributed at least 2 pups to the recordings, encompassing the age range between p5 and p13 (inclusive of odd-numbered day age groups within this range). ASD mouse models were created by administering valproic acid, an anti-epileptic drug (details given in the VPA treatment section of materials and methods). Subsequently, recordings were conducted on 12 pups, consisting of 6 males and 6 females, sourced from three distinct sets of parents, with two pups chosen from each litter. None of the animals and vocalization waveforms were excluded from the analysis. For VPA treatment females were randomly chosen not following any feature or exhibiting a particular behavior. Blinding was not needed as the process of analysis of syllables was automated except for setting the threshold above the noise floor which was confirmed by the investigators. The saline group comprised a total of 8 pups selected from three distinct sets of parents, with two pups chosen from each litter.

VPA Treatment

An adult female was checked for the estrus cycle since the chances of conception are pretty high during the estrus phase. The male and the female (in estrus) were allowed to interact for a time span of 24h (time and date noted), following which the male was separated, and the female was checked for a vaginal plug, the day considered to be the gestational day ‘0’ or embryonic day ‘0’ (E0). For creating a VPA-induced ASDs mouse model, the timed pregnant female received a single intraperitoneal injection of a freshly prepared sodium salt of VPA (NaVPA-Sigma_Life Science, P4543) at a concentration of 400 mg/kg of mouse body weight dissolved in 1X Phosphate Buffered Saline (Gibco_70011-044) with a dosing volume of 100uL on the gestational day E12.520. The mice were housed individually (left undisturbed until the pups got delivered) and allowed to raise their litter. All the VPA-based experiments were carried out on these delivered pups. The TD group had undergone no such injection procedure. The pup isolation calls (PICs) from the delivered pups were recorded from p5-p15 (on odd alternative days) and analyzed using MATLAB.

Syllables: Identification and classification

Recorded sound signals in each .wav file were bandpass filtered, removing frequencies below 30 kHz and above 160 kHz for pups. For each chunk, a short term Fourier transform was calculated using a Hanning window of length 1024 and an overlap of 75%. Syllable occurrences were identified based on power concentration and syllable classification was based on the presence or absence of a distinctive feature, pitch jump[24]. Four categories of syllable types were considered, namely S-type (S, no discontinuity in the frequency contour, no pitch jump), Jump type (J, single jump in frequency), Harmonics (H, presence of fundamental and harmonic components), and Other type (O, more than one jump in the frequency)[21,22]. A intersyllable interval of greater than 350ms was considered to be the beginning of a new bout[21].

Calculation of Joint Distributions and *MI* Based Dependence

For a syllable-to-syllable transition, joint distributions were estimated and cases with zero values were handled by applying. Krischevsky and Trofimov (KT) correction [25]. Mutual information [26] was computed based on joint distribution *P*(*X*, *Y*) and its marginal distributions *P*(*X*) and *P*(*Y*) as:

$$MI(X,Y) = \sum_{\forall X}\sum_{\forall Y} P(X=x, Y=y) log2 \frac{P(X=x, Y=y)}{P(X=x)P(Y=y)}$$

MI was calculated between the syllable in the first position with the syllable occuring in the nth position (n=1, 2, 3, …) to quantify dependency. Bootstrap[27] was used to remove bias in the estimates and a comparison was made with the scrambled version of the original one[21,22].

Kullback Leibler Divergence (*KLD*) between distributions

Information theoretic distance metric, *KLD* [21,22] was used to quantify the differences between the probability distributions as given below .

$$KLD(P||Q) = \sum_{\forall X} P(x) log2 \frac{P(x)}{Q(x)}$$

Pup Vocalisation Recording protocol

Male and female pups were individually placed on clean bedding material in a glass container (10 cm × 8 cm × 7 cm; open surface). The recording was made on postnatal days (p) p5, p7, p9, p11, and p13 for 5 minutes. After each recording, the glass container was wiped with 70% alcohol, and the bedding was changed. Acoustic signals were recorded with a free-field microphone and amplifier (1/4" microphone, Model 4939, Bruel and Kjaer, Naerum, Denmark). The acoustic signals were digitized at 375 kHz with 16-bit resolution collected with National Instruments DAQ. Recorded signal time waveforms and spectrograms were displayed in real-time on a computer with open access bioacoustics software, Ishmael.

Tracking of Informative Sequences

The calculation involved determining the significance of syllable occurrences in various positions, based on the preceding syllables[21,22]. For the initial syllable within a sequence, we calculated the likelihood of each syllable type occurring at the sequence's outset. This likelihood was then compared to the probability of each syllable type occurring with equal likelihood. Syllables exhibiting a higher probability of occurrence (with 95% confidence) than the overall average were deemed significant. This process was iterated for subsequent positions, with the preceding syllable types held constant until no more statistically significant syllables were identified. Through this approach, we identified sequences that surpassed random chance, thereby revealing underlying structural patterns.

Removal of Bias in Mutual Information Estimates and Significance Analysis

Bootstrap debiasing[28] was utilized to mitigate bias in mutual information estimates. This involved employing a resampling technique where the bootstrap dataset matched the original dataset's element count. The aim was to rectify the bias and derive confidence intervals for the debiased estimates. To gauge significance, a comparison was made between the lower and upper confidence intervals of the '0' MI estimate. This estimate was derived by deliberately scrambling the sequences, disrupting the natural transitions between syllables. This led to the estimation of '0' MI and its corresponding confidence interval from the same dataset, maintaining the same syllable count and other statistics, save for the sequence syllable order.The criterion for significance was established: if the confidence intervals of MI from the original data and the scrambled data did not overlap, the MI estimate was considered statistically meaningful. This approach effectively minimized the potential (<5%) for spurious MI due to the limitations of data size and inherent variability.

Data Availability Statement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

1. Mody M, Belliveau JW. Speech and language impairments in autism: insights from behavior and neuroimaging. *N Am J Med Sci (Boston)*, **5**, 157-161 (2013).
2. Portfors, C. V., & Perkel, D. J. The role of ultrasonic vocalizations in mouse communication. *Current opinion in neurobiology*, **28**, 115-120 (2014).
3. Semple, B. D., Blomgren, K., Gimlin, K., Ferriero, D. M., & Noble-Haeusslein, L. J. Brain development in rodents and humans: Identifying benchmarks of maturation and vulnerability to injury across species. *Progress in neurobiology*, **106**, 1-16 (2013).
4. Silverman, J. L., Yang, M., Lord, C., & Crawley, J. N. (2010). Behavioural phenotyping assays for mouse models of autism. *Nature Reviews Neuroscience*, **11**, 490-502 (2010).
5. Moore, S. J., Turnpenny, P., Quinn, A., Glover, S., Lloyd, D. J., Montgomery, T., & Dean, J. C. S. A clinical study of 57 children with fetal anticonvulsant syndromes. *Journal of medical genetics*, **37**, 489-497 (2000).
6. Williams, G., King, J., Cunningham, M., Stephan, M., Kerr, B., & Hersh, J. H. Fetal valproate syndrome and autism: additional evidence of an association. *Developmental medicine and child neurology*, **43**, 202-206 (2001).
7. Rasalam, A. D., Hailey, H., Williams, J. H. G., Moore, S. J., Turnpenny, P. D., Lloyd, D. J., & Dean, J. C. Characteristics of fetal anticonvulsant syndrome associated autistic disorder. *Developmental medicine and child neurology*, **47**, 551-555 (2005).
8. Rodier, P. M., Ingram, J. L., Tisdale, B., Nelson, S., & Romano, J. Embryological origin for autism: developmental anomalies of the cranial nerve motor nuclei. *Journal of Comparative Neurology*, **370**, 247-261 (1996).
9. Chomiak, T., Turner, N., & Hu, B. What we have learned about autism spectrum disorder from valproic acid. *Pathology research international*(2013).
10. Roullet, F. I., Wollaston, L., Decatanzaro, D., & Foster, J. A. Behavioral and molecular changes in the mouse in response to prenatal exposure to the anti-epileptic drug valproic acid. *Neuroscience*, **170**, 514-522 (2010).
11. Cheaha, D., Bumrungsri, S., Chatpun, S., & Kumarnsit, E. Characterization of in utero valproic acid mouse model of autism by local field potential in the hippocampus and the olfactory bulb. *Neuroscience research*, **98**, 28-34 (2015).

12. Schneider, T., Turczak, J., & Przewłocki, R. Environmental enrichment reverses behavioral alterations in rats prenatally exposed to valproic acid: issues for a therapeutic approach in autism. *Neuropsychopharmacology*, **31**, 36-46 (2006).
13. Kuo, H. Y., & Liu, F. C. Valproic acid induces aberrant development of striatal compartments and corticostriatal pathways in a mouse model of autism spectrum disorder. *The FASEB Journal*, **31**, 4458-4471 (2017).
14. Moldrich, R. X., Leanage, G., She, D., Dolan-Evans, E., Nelson, M., Reza, N., & Reutens, D. C. Inhibition of histone deacetylase in utero causes sociability deficits in postnatal mice. *Behavioural brain research*, **257**, 253-264 (2013).
15. Rinaldi, T., Silberberg, G., & Markram, H. Hyperconnectivity of local neocortical microcircuitry induced by prenatal exposure to valproic acid. *Cerebral cortex*, **18**, 763-770 (2008).
16. Gandal, M. J., Edgar, J. C., Ehrlichman, R. S., Mehta, M., Roberts, T. P., & Siegel, S. J. Validating γ oscillations and delayed auditory responses as translational biomarkers of autism. *Biological psychiatry*, **68**, 1100-1106(2010).
17. Mehta, M. V., Gandal, M. J., & Siegel, S. J. mGluR5-antagonist mediated reversal of elevated stereotyped, repetitive behaviors in the VPA model of autism. *PloS one*, **6**, e26077 (2011).
18. Melancia, F., Schiavi, S., Servadio, M., Cartocci, V., Campolongo, P., Palmery, M., ... & Trezza, V. Sex-specific autistic endophenotypes induced by prenatal exposure to valproic acid involve anandamide signalling. *British journal of pharmacology*, **175**, 3699-3712 (2018).
19. Tartaglione, A. M., Cipriani, C., Chiarotti, F., Perrone, B., Balestrieri, E., Matteucci, C., ... & Ricceri, L. Early behavioral alterations and increased expression of endogenous retroviruses are inherited across generations in mice prenatally exposed to valproic acid. *Molecular Neurobiology*, ***56***, 3736-3750 (2019).
20. Tsuji, C., Fujisaku, T., & Tsuji, T. Oxytocin ameliorates maternal separation-induced ultrasonic vocalisation calls in mouse pups prenatally exposed to valproic acid. *Journal of Neuroendocrinology*, **32**, e12850 (2020).
21. Agarwalla, S., Arroyo, N. S., Long, N. E., O'Brien, W. T., Abel, T., & Bandyopadhyay, S. Male-specific alterations in structure of isolation call sequences of mouse pups with 16p11. 2 deletion. *Genes, Brain and Behavior*, **19**, e12681 (2020).
22. Agarwalla, S., De, A., & Bandyopadhyay, S. Predictive Mouse Ultrasonic Vocalization Sequences: Uncovering Behavioral Significance, Auditory Cortex Neuronal Preferences, and Social Experience-Driven Plasticity. *Journal of Neuroscience* (2023).
23. Grimsley, J. M., Monaghan, J. J., & Wenstrup, J. J. Development of social vocalizations in mice. *PloS one*, **6**, e17460 (2011).
24. Holy, T. E., & Guo, Z. Ultrasonic songs of male mice. *PLoS biology*, **3**, e386(2005).
25. Krichevsky, R., & Trofimov, V. The performance of universal encoding. *IEEE Transactions on Information Theory*, **27**, 199-207 (1981).
26. Cover, T. M., & Thomas, J. A . Elements of Information theory, Second. John Wiley & Sons, Inc.,Hoboken,New Jersey (2006).
27. Efron, B., & Tibshirani, R. J. An introduction to the bootstrap. CRC press (1994).

Supplementary Figure

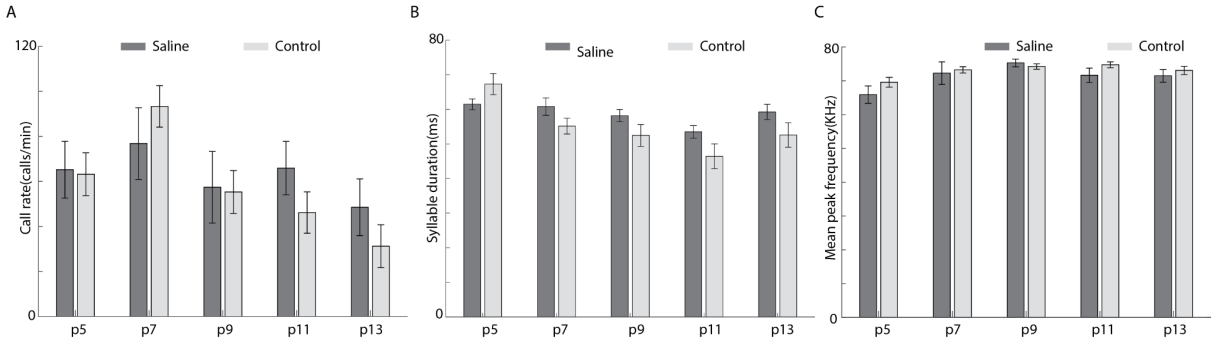

Figure S1: Comparative analysis of acoustic features over developmental age between Saline and Control

Comparative study of the A) Call rate B) Syllable duration distribution C) Mean peak frequency Repeated measure ANOVA with Post-hoc analysis by Tukey multiple comparisons. No significant difference observed for the acoustic features.