Intact Representation of Vocal Smile in Autism: A reverse correlation approach

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Abstract

Atypical emotional prosody production and perception have been reported in autism. However, it is unclear whether these particularities are associated with unusual mental representations of vocal emotions. The objective of the current study was to explore the mental representation of vocal smile in autistic adults. Twenty-nine autistic (ASD) and 29 neurotypical (NT) adults performed an auditory reverse correlation task, that affords the opportunity to extract acoustic features of mental representation and their variability. Most ASD participants (17) based their representation of vocal smile on similar acoustic features as NT participants and no difference in the level of internal noise was observed. However, comparisons between groups revealed a more typical representation in NT than in ASD. Subsequent cluster analysis revealed that the difference of typicality was explained by a small subset of ASD participants displaying different representations. A correlation analysis also revealed that the typicality was positively correlated with the empathetic level within both groups. While most autistic adults have a preserved mental representation of vocal smiles, a subset shows less robust and typical representations, which is linked to lower levels of empathy. This study highlights that the perception of vocal smiles in autism is more nuanced than previously reported, with empathy playing a substantial role in shaping these mental representations.

Keywords

Autism, Prosody, Vocal smile, Reverse Correlation, Internal noise

1. Introduction

Prosodic atypicalities are considered as a core central feature of communication profile in autism. In particular, atypicalities in emotional prosody (i.e., vocal emotion) perception and production in children (McCann & Peppé, 2003; Peppé et al., 2007) but also in adults (Hubbard et al., 2017) have been widely studied since the original descriptions of Kanner and Sukhareva (Andronikof & Fontan, 2016; Kanner, 1943). An early hallmark in autism is also a lack of response to (Beall et al., 2008) and production of (Dawson et al., 1990) social smile, one of the most emblematic expression of the human emotional repertoire. Understanding and evaluating mental representation of vocal smile in autism should give keys in the comprehension of prosody atypicalities in autism.

Behavioral studies in autism have shown difficulties in recognition of others prosodic intention (see Leung et al., 2022 for a review). However, pitch discrimination in autism has been described as better than in neurotypical individuals for non-vocal sounds (Bonnel et al., 2003, 2010; Heaton et al., 2008) with also a larger proportion of absolute pitch in the autistic population (Miller, 1999; Rimland & Fein, 1988). Nevertheless, these improved auditory skills in autism are not sufficient for efficient recognition of vocal emotions, suggesting that atypical prosodic processing does not arise from sensory processing difficulties, but rather from subsequent integrative processes enabling the attribution of meaning to specific and voice patterns.

Perceptive representation of several stimulus categories have been extracted from physical features through the reverse correlation technique, historically in the visual modality (Ahumada & Lovell, 1971), but has recently gained in influence in the auditory modality (Adl Zarrabi et al., 2024; Goupil et al., 2021; Merchie et al., 2024; Ponsot, Arias, et al., 2018; Ponsot, Burred, et al., 2018; L. Wang et al., 2022). Smile could be identified from vocal cues (Aubergé & Cathiard, 2003; Tartter, 1980; Tartter & Braun, 1994) and thanks to reverse correlation, a robust acoustic model of vocal smile was revealed, which even led to motor resonance in neurotypical adults (Arias et al., 2018; Merchie et al., 2024). Vocal smile internal representation is characterized by an upward shift in frequency of formants F1 and F2, and an increase in energy of F2, F3 and F4 compared to neutral voice (Ponsot, Arias, et al., 2018), reflecting the modulation of vocal tract induced by the bilateral contraction of the Zygomaticus major muscles during smile (Wood et al., 2016). Few studies, however, have used this technique to characterize mental representations in autism, neither in the visual nor in the auditory modality. In a visual reverse correlation "Bubbles" task, results suggested that autistic children did not use the same information than neurotypical during identity judgment (Ewing et al., 2018). However, another study demonstrated that to identify positive emotion, contrary to eye tracking studies (Black et al., 2017), ASD children correctly used the information from the eyes region (Song et al., 2012). Only one study used an auditory reverse correlation paradigm in autistic children, and observed similar representations of rising pitch in speech and complex tone, and musical melody contours (L. Wang et al., 2022). No study gets yet interested in the evaluation of acoustic cues used in the classification and representation of vocal emotion in autism.

Both neural and behavioral intra-subject variability have been proposed to contribute to sensory symptoms in ASD (Magnuson et al., 2020; Ward, 2019). Whether this variability also impacts internal representations remains to be explored. Mental representation of specific features could be altered by internal noise leading to difficulty in processing signal. Noise is always present in processing signal through external (Brinkman et al., 2017) or internal noise (Neri, 2010). In reverse correlation studies, the internal noise referred partly to "intrinsic noise in the decision making" and could be estimated in reverse correlation task through the double pass-paradigm (i.e., repetition of 2 blocks of identical stimuli to estimate response variability) (Ponsot, Arias, et al., 2018). Few studies used the double-pass methodology to estimate internal noise in autism, but they reported an increased level during a visual task (Park et al., 2017; Vilidaite et al., 2017) or no difference with an audio reverse correlation protocol compared to neurotypicals (L. Wang et al., 2022).

The main objective of the current study was to characterize the perceptive representation of vocal smile in a group of autistic adults with an adapted reverse correlation paradigm and to compare it to the robust neurotypical model (Merchie et al., 2024; Ponsot, Arias, et al., 2018), through the calculation of the representation typicality (i.e., standardized distance between representations) taking as a reference Ponsot et al.'s model (2018). This will enable us to determine whether autistic people rely on the same acoustic cues as those of neurotypicals to classify a voice as smiling. This paradigm also allowed to estimate internal noise in the same groups thanks to double-pass methodology. Combination of mental representation typicality and internal noise indices should give the opportunity to extract different profiles in autistic adults and to link these profiles to clinical information. This study with these different measures thus informs on both the typicality and the robustness of the representations of emotional prosody in autistic adults.

2. Material and methods

2.1. Population

Thirty autistic and 29 non-autistic participants participated in the current study. Autistic adults were recruited through the Autism Resource Center of Centre Val de Loire and diagnosed by a trained clinical team according to DSM-5 criteria. Diagnosis was confirmed with ADOS-2 and ADI-R (Lord et al., 1994, 2000). Verbal and non-verbal efficiencies were estimated through the use of selected subtests of the WAIS-IV (Wechsler, 2012) for neurotypicals, while the entire scale was proposed to autistic participants. The Autism Quotient 50-questions (AQ) and the Empathy Quotient 40-questions (EQ) were proposed to all the participants (Baron-Cohen et al., 2001; Baron-Cohen & Wheelwright, 2004). One participant was discarded in the autistic group because of a doubt about diagnosis and another participant who was not able to complete the task. The group of non-autistic adults reported an absence of any developmental difficulties in language and sensorimotor acquisition. In both groups, no disease of central nervous system, infectious or metabolic diseases, epilepsy, or an abnormal audition was reported. Participant's audition was checked for both ear with a short subjective audiometry test. Every participant (or their legal guardian in case of adult under guardianship) signed an informed consent form, and the protocol received approval from Ethic Committee (PROSCEA 2017/23; ID RCB: 2017-A00756-47). A description of the two groups is presented in table 1.

(INSERT TABLE 1)

2.2.Sound modulations

The same method and stimuli as in Ponsot et al. (2018) have been used to evaluate mental representation of vocal smile in both group. In brief, the French phoneme /a/ uttered by a male speaker with a constant pitch was recorded. To obtain a constant spectral energy a 500ms stationary part of the sound was selected. Then, the sound was modulated, to create multiple variants, in 25 frequencies between 100 and 10,000Hz with random gain values (in dB) from a Gaussian distribution with the Cleese python toolbox (Burred et al., 2019).

2.3.Procedure

The current experiment took place in a larger session (~1h30) of testing for most of the participants. The sequence of stimulation for the reverse correlation task was composed by 200 trials for autistic (~15min) and 300 trials for non-autistic (~20min) divided in blocks of 50 trials. Each trial consisted in a pair of randomly-filtered voice to be compared to estimate the most smiling voice between both presented. Participants had to choose the most "smiling" sound of each presented pair by pressing a key. The last two blocks were identical to evaluate internal noise through the double-pass methodology. Consequently, the number of trials for estimating mental representation of vocal smile was 150 for autistic and 250 trials for non-autistic.

To estimate the minimum number of trials required to obtain a reliable representation of the vocal smile, a convergence analysis was carried out, revealing that 150 trials appeared sufficient for this estimation. However, in order to obtain a robust control representation from the model of the non-autistic participants, we decided to lengthen the sequence by adding 2 blocks of 50 trials each.

2.4.Reverse correlation analysis

Mental representation

The mental representation of vocal smile was modelled for each participant with the classification image technique. The mean pitch contour of voice classified as “unsmiling” was subtracted from the mean pitch contour of “smiling” voice. Then, the resulting representation was normalized by dividing it by the sum of their absolute value. A model of each participant’s model was then computed and averaged by group. A comparison between NT and ASD’s gain was performed in each modulated frequency.

To estimate the deviation of participant model to the model of an external control group (Controls) (Ponsot, Arias, et al., 2018) the distance between the average group representation and the participant was computed and then normalized in both groups (‘representation typicality’) (see Equation 1). Representations for non-autistic were computed using the same procedure, using only the first 150 trials of each session in order to match the number of trials seen by patients.

$$(1)\ distance = \sum_{f=100}^{10,000} \left| Gain_{f,controls} - Gain_{f,participant} \right|$$

$$(2)\ typicality = 1 - \frac{distance - \min(distance)}{\max(distance) - \min(distance)}$$

Equation 1: (1) Calculation of the distance between the Controls model and one participant’s model as sum of the absolute difference of model's gains for each of the 25 modulated frequencies (f) between 100 and 10,000 Hz. (2) Calculation of the typicality as the normalization of the distance between 0 and 1 between NT and ASD.

Internal noise

The same method as in Adl Zarrabi et al. (2024) has been used to evaluate internal noise (expressed in units of the standard deviation of stimulus noise) from response consistency (probability of agreement , p-agree) and response bias (p-int1) between the two repeated blocks using the simulation procedure of Neri (2010). Then for each participant a reverse model was applied to obtain the value of internal noise minimizing the error between the observed and the simulated values for a participant's consistency and bias (Internal Noise). As in Neri (2010) internal noise was estimated in the [0 ; 5 std] range to avoid unreliable large value.

Internal noise was computed using the open-access python toolbox "palin" (https://github.com/neuro-team-femto/palin). Data from one autistic participant were removed for internal noise estimation because the repeated block was not completed.

2.5.Statistical analysis

Statistical analyses were conducted on RStudio 4.0.4 (R. C. Team, 2021; Rs. Team, 2020) with the packages ggplot2 (Wickham, 2016), ggpubr (Kassambara, 2020), dplyr (Wickham et al., 2021), tidyverse (Wickham et al., 2019) and factoextra (Kassambara & Mundt, 2017).

In order to compare mental representation and noise between groups, Student's tests were performed for representation typicality, p-agree, p-int1 and internal noise. Pearson's correlation between scores in questionnaires (AQ and EQ) or clinical scores (ADOS score, the sum of communication and social interaction) and the different indices of the reverse correlation results were also performed. A global correlation analysis was performed when scores were available for both groups to reflect the effect of the autistic traits and empathy in a continuum, after Fisher's z-tests have been performed to confirm that there was no statistical difference between groups in correlation coefficients. As multiple correlations were calculated the p-value was Bonferroni's corrected and the corrected values were reported.

2.5.1. Cluster analysis

To evaluate the potential different profiles in participants a cluster analysis based on both mental representation (representation typicality) and noise (internal noise) was performed. Variables were scaled for normalization for both groups. A K-means clustering method was chosen (see Manenti et al., 2024 for a detailed description of the methods to determine the best number of clusters). A qualitative description of the different clusters obtained was presented.

3. Results

3.1. Reverse correlation analysis

3.1.1. Mental representation of vocal smile

A Student’s test has been performed on each frequency between groups (ASD vs NT) to evaluate potential differences in mental representation of vocal smile in acoustic description (Figure 1). As the number of comparisons was quite large (25 frequencies) a Bonferroni correction was applied. No difference between the mental representation in ASD and NT has been revealed.

(INSERT FIGURE 1)

In both group representation of vocal smile was characterized by an upward switch in frequency of F1 and F2, and by an energy increase of F2 and F4.

Representation typicality

Representation typicality was calculated according to the distance to the model of the Controls group with 600 trials (Ponsot, Arias, et al., 2018). The typicality of the model appears significantly different between NT and ASD group ($t(52) = 2.20$; $p < .05$, see Figure 2a), suggesting that mental representation of the NT was closer to these of the external Control’s than the one of the ASD. Nevertheless, participants with autism used relevant frequency modulations to classify a vocal smile, and the typicality differences observed is mainly related to irrelevant frequency modulations (< F1 frequency, 555 Hz).

(INSERT FIGURE 2)

To evaluate if a relation between clinical scores and the representation typicality existed in the ASD group, a correlation analysis was performed with the ADOS score but did not reveal any significant result ($r = -.03$, $p = .91$). Neither was the correlation coefficient between typicality and AQ in NT ($r = .03$ ($p = .87$)), nor in ASD ($r = -.09$ ($p = .66$)) significant. Fisher's z-tests conducted to compare the correlation coefficients between two independent samples did not reveal any statistical difference ($z = .42$, $p = .68$).

The correlation between representation typicality and EQ in NT and in ASD were respectively r = .31 (p = .13) and r = .21 (p = .32). The Fisher's test revealed no statistical difference between the two correlation coefficients (z = .38, p = .71). Considering that there was no significant difference in correlation coefficients between groups, a joint analysis of the correlation between AQ or EQ scores and typicality was conducted on the whole population. There was no correlation with AQ score (r = -.22, p_{corr} = .26) but a significant correlation between the EQ score and the typicality was identified (r = .34, p_{corr} = .03, see Figure 2b). The higher the EQ score, the more similar the acoustic smile representation is to that of the Controls group.

3.1.2. Internal noise

To evaluate differences between NT and ASD internal noise, Student's tests were performed to compare p-agree, p-int1 and the estimated internal noise. These comparisons revealed no difference for p-agree (t(53) = .66 ; p > .1), internal noise ((37) = -1.29 ; p > .1, see Figure 3a) and p-int1 was revealed (t(54) = 1.79 ; p < .1).

(INSERT FIGURE 3)

Then, as for the typicality, correlation analysis between internal noise and ADOS, AQ and EQ were performed with the same method, and none reached significance. No correlation with ADOS score in ASD group was observed (r = .04, p = .87).

The correlation coefficient between internal noise and AQ in NT was r = .04 (p = .85), and in ASD was r = .32 (p = .12). No statistical difference between the two correlation coefficients, z = -.97, p = .33 was revealed.

The correlation coefficient between internal noise and EQ in NT was r = -.43 (p = .03), and in ASD was r = -.06 (p = .77), but not different statistically (z = -1.29, p = .19). Considering that there was no significant difference in correlation coefficients between groups, a joint analysis of the correlation between AQ or EQ scores and internal noise was conducted. A tendency to a positive correlation between the internal noise and the AQ was observed (r = .30, p_{corr} = .06, see Figure 3b), the higher the AQ score the higher the internal noise estimated, but there was no correlation with EQ score ($r = -.24$, $p_{corr} = .18$).

Cluster analysis

3.1.3. Clusters definition

The optimal number of clusters was automatically estimated to be three in our sample with the k-means method with a Hopkins statistic of .72 (above the threshold .5) with representation typicality and internal noise (IN) as factors. The profiles were qualified as: *Typical representation – Low IN*, *Atypical representation – Low IN* and *High IN* and are described in table 2. Clusters are presented with an “illustrative” patient for each cluster in figure 4.

(INSERT FIGURE 4)

As NT and ASD were considered together in the cluster analysis, the distribution of group in each cluster was compared and no significant association between group and cluster distribution was observed ($p = .37$; Fisher's Exact Test ; FET).

Comparisons of clinical scores for ASD patients were performed between clusters but did not reveal any statistical differences.

3.1.4. Qualitative description of clusters

Considering the relatively small size of clusters a qualitative description was performed to evaluate the differences and the clinical implication of these three profiles (table 2). First, the *Typical representation – Low IN* group includes almost the entire group of neurotypical adults (23/29) and a majority of the ASD (17/27) group indicating that as in Ponsot et al. (2018), the internal representation of vocal smile was stable and robust in most NT and ASD adults. However, the fact that a small number of typical adults do not have the same profile of vocal smile and associated internal noise, shows that heterogeneity also exists in the general population. No difference in clinical scores was observed between clusters, but the size of the two alternative clusters (*Atypical representation – Low IN* and *High IN*) did not allow to perform correct statistical analysis.

(INSERT TABLE 2)

Looking at the representations of vocal smile in the *Typical representation – Low IN* revealed that the acoustic cues used to identify a vocal smile were very similar regardless the group (figure 5a). In contrast, the *Atypical representation – Low IN* models were noisy and did not base their representation of smile on the same acoustic cue. The autistic participants in this group used the inverse information to classify a sound as smiling in comparison to Controls group (figure 5b). Finally, in the *High IN* cluster, acoustic cues were not that different from the Controls' model but considering the high internal noise in these participants, interpreting their models remains challenging (Figure 5c).

(INSERT FIGURE 5)

4. Discussion

This study was the first to characterize mental representation of emotional prosody, a particularly challenging feature, in autism with an emotional auditory reverse correlation paradigm. Results revealed that a large majority of autistic participants based their representation of vocal smile on the same acoustic features as neurotypicals do. However, differences in the perceptive representation of vocal smile in a subgroup of autistic adults in comparison to neurotypical, but also a larger internal noise in another subgroup of autistic participants, have been observed.

4.1.Preserved mental representation of vocal smile

The majority of autistic participants (17/27) used the same acoustic cues in their mental representation of vocal smile as neurotypical with a robust model (low IN). This result suggests that the representation of the vocal smile is shared by all and preserved in most autistic adults. This is in line with studies that reported no difference in the recognition of emotional prosody neurotypical and autistic participants (Brennand et al., 2011; Brooks & Ploog, 2013; Chevallier et al., 2011; Grossman et al., 2010; Paul et al., 2005). However, some other studies showed difficulties in emotional prosody recognition in autism (Hubbard et al., 2017). Cluster analysis revealed a profile of autistic participants with an atypical representation of vocal smile with limited internal noise, that might contribute to the lower typicality of the internal representation of smile in the ASD group as a whole. This also suggests that difficulties in emotion recognition reported in some studies, might be the consequence of the heterogeneity of the models in some autistic participants.

The current study estimates mental representation of vocal smile based on low-level acoustic analysis and it has been shown that for non-vocal acoustic processing, autistic adults display better skills than neurotypicals (Bonnel et al., 2003, 2010; Heaton et al., 2008). One can hypothesize that studies which report low emotional prosody recognition in autism, used more ecological stimuli and tasks that required higher-level processes than in the present study. The current results demonstrated that the low-level representations of emotional prosody are intact in autism, but one can not exclude that more spontaneous mechanisms as automatic recognition and judgment could be atypical.

In a previous study, even if difficulties in happiness prosody recognition were reported, a positive association between a good recognition of happiness prosody and a better social adaptation was observed (J.-E. Wang & Tsao, 2015). This relation was not observed between representation typicality and ADOS score in the autism group in the present work, but a positive correlation between the empathetic abilities and the typicality was found. These relationships demonstrated the importance of low-level acoustic processing of emotional prosody in social abilities. Perhaps empathetic abilities, that reflect the ability to understand and share the feelings of other, refine the emotional prosody acoustic processing in neurotypical and autistic adults, or conversely that a typical representation of emotional prosody allows better relations to others and thus develop greater empathy.

4.2.Internal noise

At group level, no difference in internal noise was observed between NT and ASD participants. This lack of difference is compatible with some theories for which noise is not different in autism (Davis & Plaisted-Grant, 2015), but also with the results of a previous reverse correlation study in auditory modality in autistic children in which no difference was shown (L. Wang et al., 2022).

Nevertheless, cluster analysis revealed a subgroup of participant with a *High IN*, mainly composed by autistics (6 ASD vs 3 NT). In this profile the mental representation of vocal smile is similar to Ponsot's results (2018) suggesting that i) unstable noisy representation could lead to both prosody difficulty and hypo- or hyper-sensitivity in autism and ii) the quantity of internal noise is not related to the quality of the representation of vocal smile. Indeed, for some authors a larger internal (neural) noise might facilitate the detection and discrimination of signal (Davis & Plaisted-Grant, 2015). Nonetheless, in this profile the larger IN (> 3) were observed in four autistic participants only, a result that should be considered with caution. The heterogeneous results between participants with autism in terms of internal noise levels also reflect the diversity of participants' clinical profiles. Moreover, even in the absence of significant relationships between internal noise level and clinical measures it should be noted that the autistic participants with larger level of intra-individual variability had high ADOS and AQ scores, reflecting greater autistic symptoms.

Finally, in the context of the Bayesian brain, the difference in internal noise level and mental representation modify the perception of the environment (Haker et al., 2016). The present study offered the possibility to estimate an outline of the mental representation to which the percept is compared, in a Bayesian context, and of the noise that would modulate this representation. In autism the Bayesian theories proposed that the sensory input and the prediction (mental representation) differ in weight, which leads to hypo- or hyper-sensitivity (Brock, 2012; Haker et al., 2016; Lawson et al., 2014; Van de Cruys et al., 2014). The level of noise in the signal and internal noise have been proposed to influence the level of prediction of the sensory input according to the context, and thus noisy inputs would lead to hyposensitivity and precise input to hypersensitivity (Van de Cruys et al., 2017).

4.3. Limitations and perspectives

In the present study, the available clinical measures (ADOS, AQ) did not explain the different profiles. The addition of hyper- and/or hypo-sensitivity assessment, as the Dunn sensory profile (Kern et al., 2007) or the Glasgow Sensory Questionnaire (Robertson & Simmons, 2013) for example, would provide complementary information on the internal noise profiles observed. Moreover, to draw stronger conclusions on the association between clinical measures and the observed profiles, the inclusion of more participant in the alternative experimental profiles (*Atypical representation – Low IN* and *High IN)* is required, considering, however, that in this study more participants were included than in previous studies of reverse correlations carried in the auditory modality (30 participants in each group versus 10 to 20 in other studies) (Adl Zarrabi et al., 2024; Goupil et al., 2021; Ponsot, Arias, et al., 2018; Ponsot, Burred, et al., 2018). Because the reverse correlation task was a part of a larger protocol, the addition of another task was not possible and thus, no measure of emotional prosody production has been performed. Thought it could have informed on the implication of different representation of vocal emotion on the production. In fact, it has been shown that the measurement of certain acoustic indices during prosodic productions (frequency of F0 and formants and mean Harmonic to Noise Ratio, among others) enables a precise and sensitive classification according to a diagnosis of autism in children (Briend et al., 2023). Combining this information with the acoustic indices of the mental representation of vocal smile could enable this classificatory analysis to be extended.

Musical practice has been shown to enable a finer analysis of the acoustic signal (Molnar-Szakacs & Heaton, 2012), and this could have a beneficial effect on the development of vocal emotion representation in autism (Redondo Pedregal & Heaton, 2021). This finer acoustic analysis might play a role in the analysis of sounds with added social content. Unfortunately, such a detailed analysis of musical practice was not possible in the tested sample due to an insufficient number of musician participants (11/29 in the NT and 8/28 in the ASD group). In the future, it would be interesting to include more musician participants in order to test these potentially beneficial effects on perceptive representations of vocal emotions.

5. Conclusion

To summarize, this study allowed to estimate mental representation of vocal smile, and the internal noise level associated in a clinical population with a short and simple paradigm highlighting fairly preserved processes in autistic adults. This study however revealed different profiles according to both mental representation and internal noise that could contribute to difficulties in recognition and response to emotional prosody in some autistic individuals. Measurement of emotional contagion evoked by prosodic voices in autism should allow to go further in the understanding of prosody atypicalities in the autistic participants who display typical and robust perceptive representation.

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Figure Captions

Figure 1. Mental representation of vocal smile in ASD (blue) and NT (orange). The “Controls” group (black) corresponds to data from Ponsot et al. (2018) with 600 trials. Dashed lines represent formants frequencies.

Figure 2. Typicality of the mental representation of vocal smile. a: typicality of the vocal smile representation to Controls in NT (orange) and ASD (blue) group * p > .05; b: correlations between typicality and EQ in ASD and NT groups, the fine colored lines correspond to separated group analysis, the bold black line is the correlation within groups.

Figure 3. Internal noise estimation. a: internal noise in NT (orange) and ASD (blue) group * p > .05; b: correlations between internal noise and AQ in ASD and NT groups, the fine colored lines correspond to separated group analysis, the bold black line is the correlation within groups.

Figure 4. Cluster analysis according to typicality and internal noise in ASD (cross point) and NT (dot point) and an example of a representative patient of each cluster in the chosen color of the clusters. Typical representation – Low IN (blue); Atypical representation – Low IN (grey) and High IN (yellow). The black curve represents the Controls representation of vocal smile. IN: internal noise.

Figure 5. Mental representation of vocal smile in each cluster for NT (orange) and ASD (blue) in comparison to the Controls model (black) with 600 trials. IN: internal noise a: Typical representation and low IN cluster; b: Atypical representation and low IN cluster; c: High In cluster

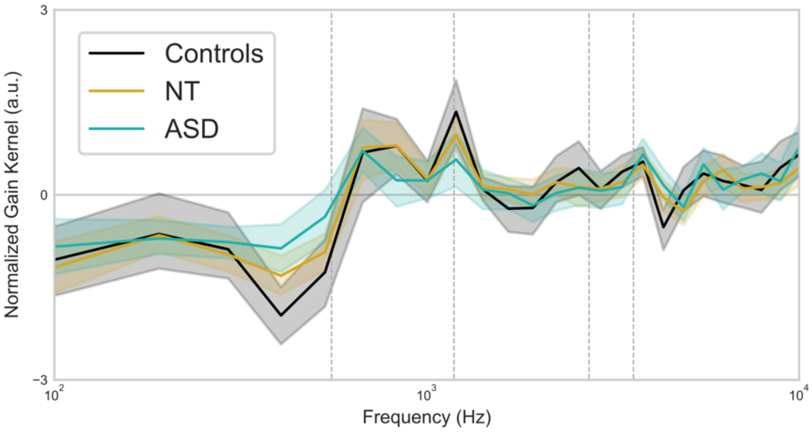
Controls
NT
ASD
Normalized Gain Kernel (a.u.)
3
0
−3
10^2
10^3
10^4
Frequency (Hz)

Figure 1

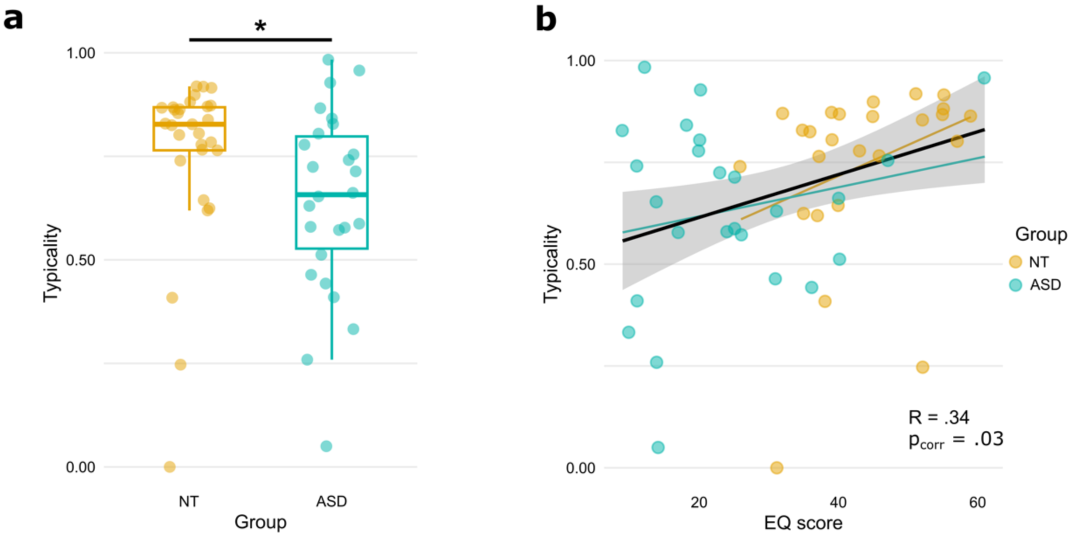
a
*
1.00
0.50
0.00
Typicality
NT
ASD
Group
b
1.00
0.50
0.00
Typicality
20
40
60
EQ score
Group
NT
ASD
R = .34
p_{corr} = .03

Figure 2

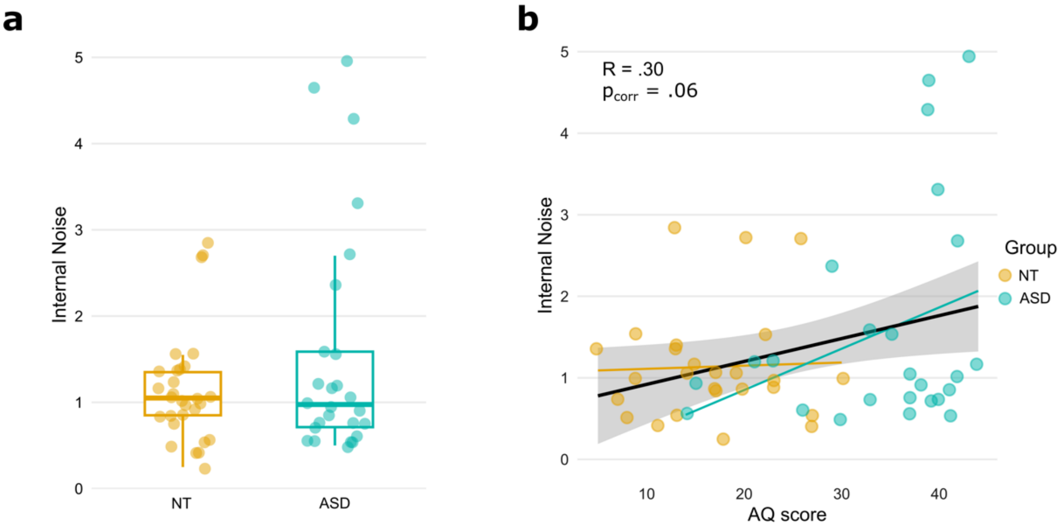
a
Internal Noise
0
1
2
3
4
5
NT
ASD
b
R = .30
p_corr = .06
Internal Noise
0
1
2
3
4
5
10
20
30
40
AQ score
Group
NT
ASD

Figure 3

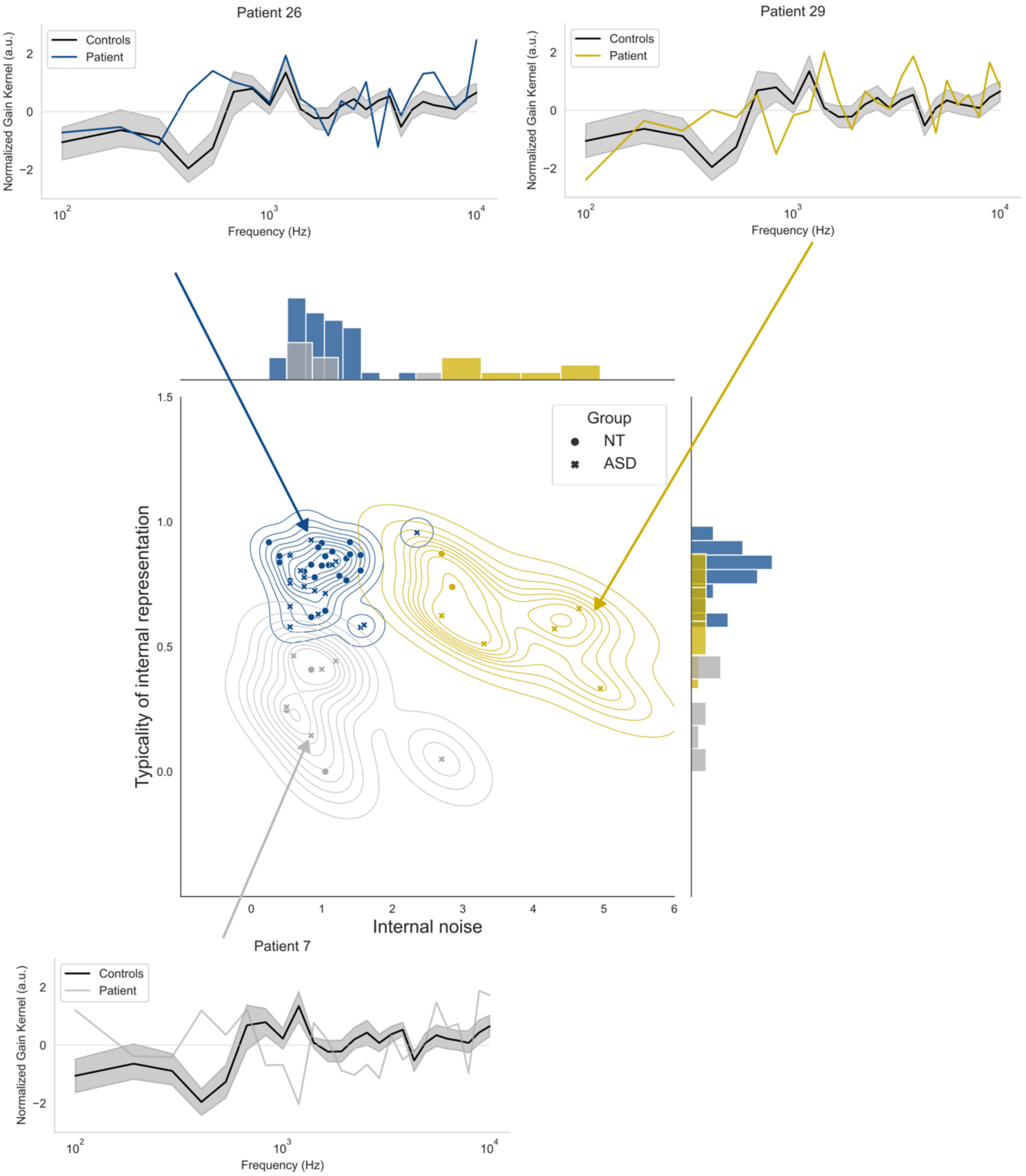
Patient 26
Controls
Patient
Normalized Gain Kernel (a.u.)
2
0
−2
10^2
10^3
10^4
Frequency (Hz)
Patient 29
Controls
Patient
Normalized Gain Kernel (a.u.)
2
0
−2
10^2
10^3
10^4
Frequency (Hz)
Group
NT
ASD
Typicality of internal representation
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
Internal noise
Patient 7
Controls
Patient
Normalized Gain Kernel (a.u.)
2
0
−2
10^2
10^3
10^4
Frequency (Hz)

Figure 4

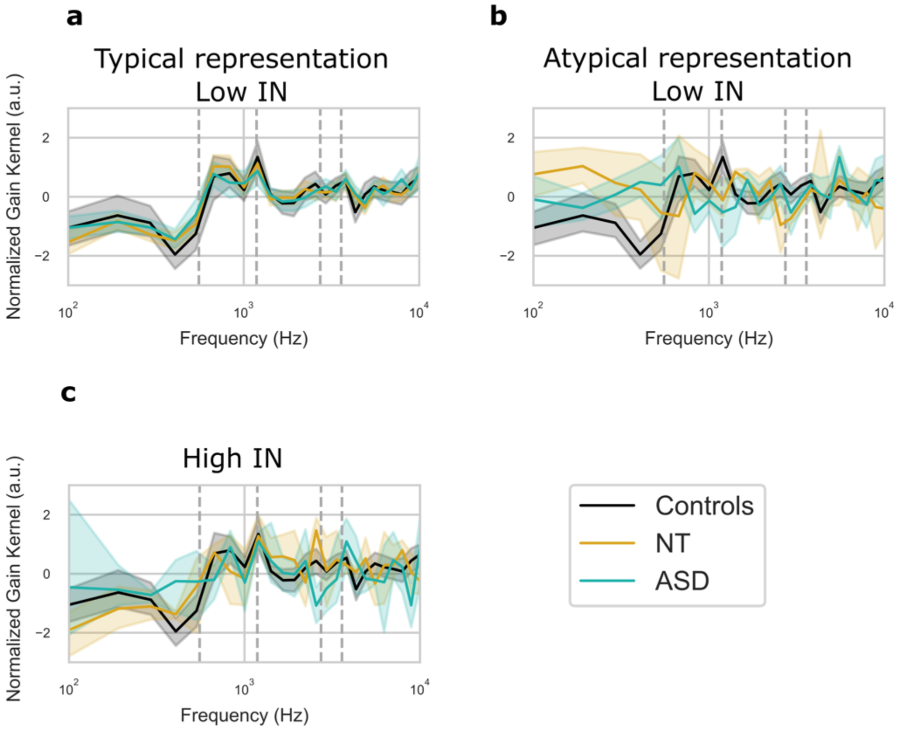
a
Typical representation
Low IN
b
Atypical representation
Low IN
c
High IN
Normalized Gain Kernel (a.u.)
2
0
−2
10^2
10^3
10^4
Frequency (Hz)
Controls
NT
ASD

Figure 5

Tables

	NT	ASD	Comparison
Sex	12 ♀ 17♂	7 ♀21♂	χ^2 =1.06 ; p =.30
Age	30.1 ± 12	35.3 ± 13	t(54) = -1.55 ; p = .13
vIQ	124.2 ± 11 (24)	118.3 ± 20 (25)	t(40) = 1.30 ; p = .20
nvIQ	106.3 ± 12 (24)	100.7 ± 18 (25)	t(44) = 1.32 ; p = .19
AQ	16.8 ± 7 (23)	34.9± 9 (25)	t(47) = -8.30 ; p < .0001
EQ	43.2 ± 9 (23)	23.7 ± 13 (25)	t(45) = 6.31 ; p < .0001
ADOS	/	8.8 ± 5.5	/

Table 1. Characteristics of Neurotypical (NT) and Autistic (ASD) group (mean ± standard deviation). vIQ : verbal Intelligence Quotient calculated from the WAIS-IV in ASD, and composite score calculated from vocabulary and similarities subtests in NT. nvIQ : non-verbal Intelligence Quotient calculated from the WAIS-IV in ASD, and composite score calculated from matrix reasoning and cubes subtests in NT. ADOS: score calculated as the sum of the subdimensions communication and social interaction behaviors. The values in brackets correspond to the number of values included in the calculation of the mean and standard deviation due to missing data.

	Typical representation Low IN		**Atypical representation Low IN**		**High IN**	
Group	**NT**	**ASD**	**NT**	**ASD**	**NT**	**ASD**
n	23	17	3	6	3	4
Age	31.4 ± 13.6	32.3 ± 12.1	25.6 ± 1.4	41.4 ± 13.2	24.7 ± 2.8	39 ± 13.2
vIQ	124.4 ± 11.5 (18)	117.4 ± 18.8 (14)	119.7 ± 12.1	117.7 ± 22	127.3 ± 8.6	120.5 ± 30.6
nvIQ	105.9 ± 13.9 (18)	103.8 ± 16.8 (14)	108.7 ± 4.2	95.8 ± 20	106.7 ± 4.6	94.5 ± 23.9
AQ	16.6 ± 7 (20)	33.5 ± 9.0 (16)	15 ± 6.2	35 ± 10.9	19.7 ± 6.5	40.3 ± 2.1
EQ	45.2 ± 8.5 (19)	25.2 ± 13.8 (16)	40.3 ± 10.7	20.5 ± 10.4	33.3 ± 6.7	22.5 ± 13.5
Internal noise	1 ± 0.4	1 ± 0.5	0.8 ± 0.3	1.1 ± 0.8	2.8 ± 0.1	4.3 ± 0.7
ADOS	/	8 ± 5.2	/	10.7 ± 5.5	/	9.3 ± 7.1
Representation typicality	0.8 ± 0.1	0.8 ± 0.1	0.2 ± 0.2	0.3 ± 0.2	0.7 ± 0.1	0.5 ± 0.1

Table 2. Description of clusters in ASD and NT (mean ± standard deviation). The values in brackets correspond to the number of values included in the calculation of the mean and standard deviation due to missing data. IN: internal noise.

Statements and Declarations

Funding

This work was supported by the INSERM (National Institute for Health and Medical Research). Annabelle Merchie was funded by the FEANS (Fondation Européenne pour l'Avancement des Neurosciences) and the Agence Nationale de la Recherche (ANR-19-CE37-0022-01). The funding sources were not involved in the study design, data collection and analysis, or the writing of the report.

Competing interests

All authors declare that they have no conflicts of interest.

Ethics approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The protocol received approval from Ethics Committee (PROSCEA2017/23; ID RCB: 2017-A00756-47).

Consent to participate

Informed consent was obtained from all individual participants (or their legal guardian in case of adult under guardianship) included in the study.

Data and code availability

Please contact the corresponding author for data and experimental stimuli requests.

Author's contributions statements

Annabelle Merchie, Jean-Julien Aucouturier and Marie Gomot designed the study. Emmanuelle Houy-Durand was responsible for the recruitment and the clinical assessment of patients. Annabelle Merchie and Zoé Ranty performed data acquisition. Annabelle Merchie, Zoé Ranty, Aynaz Adl Zarrabi, Jean-Julien Aucouturier and Marie Gomot were responsible for data and statistical analyses. Annabelle Merchie, Jean-Julien Aucouturier and Marie Gomot wrote the first version of the manuscript. All authors were involved in preparing and reviewing the manuscript.