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Title

Sounds pleasantness ratings in autism: interaction between social information and acoustical noise level.

Authors

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Abstract

A lack of response to voices, and a great interest for music are part of the behavioral expressions, commonly (self-)reported in Autism Spectrum Disorder (ASD). These atypical interests for vocal and musical sounds could be attributable to different levels of acoustical noise, quantified in the harmonic-to-noise ratio (HNR). No previous study has investigated explicit auditory pleasantness in ASD comparing vocal and non-vocal sounds, in relation to acoustic noise level. The aim of this study is to objectively evaluate auditory pleasantness. 16 adults on the autism spectrum and 16 neuro-typical (NT) matched adults rated the pleasantness of vocal and non-vocal sounds, with varying harmonic-to-noise ratio levels. A group by category interaction in pleasantness judgements revealed that participants on the autism spectrum judged vocal sounds as less pleasant than non-vocal sounds; an effect not found for NT participants. A category by HNR level interaction revealed that participants of both groups rated sounds with a high HNR as more pleasant for non-vocal sounds. A significant group by HNR interaction revealed that people on the autism spectrum tended to judge as less pleasant sounds with high HNR and more pleasant those with low HNR than NT participants. Acoustical noise level of sounds alone does not appear to explain atypical interest for voices and greater interest in music in ASD.

Keywords

ASD ; voice perception ; pleasantness ; harmonic-to-noise ratio; (non-)vocal sounds

38 Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder, characterized by deficits
39 in communication and social interaction and specific, repetitive patterns of behavior, interests
40 or activities (American Psychiatric Association, 2013). In line with these social deficits, the
41 clinical observations of individuals on the autism spectrum often report atypical behaviors in
42 response to sounds, and voices in particular, such as a lack of interest and/or response to voices,
43 echolalia and hypo or hyper sensitivity to auditory stimuli (American Psychiatric Association,
44 2013; Kanner, 1943). Accordingly, it was reported that autistic people, in particular those
45 without intellectual disability, fail to extract vocal indices about the mental state of others
46 (Rutherford et al., 2002). Note that, following recommendations by Bottema-Beutel et al.
47 (2021), we choose to use people “on the autism spectrum”, or “autistic people” to refer to
48 autistic individuals.

49 The human voice is an important tool for social interaction, because it holds information about
50 a speaker’s gender, identity (Belin et al., 2011) and emotional state (Belin et al., 2004).

51 The Temporal Voices Areas (TVA), a cerebral network specialized in human voice processing
52 are characterized by a preferential response to voices than other non-vocal sounds (Belin et al.,
53 2000). This preferential activation of the TVA is thought to be the origin of the positive wave
54 specific to voices recorded with electroencephalography (EEG) over fronto-temporal areas, the
55 fronto-temporal positivity to voices (FTPV; Capilla et al., 2013; Charest et al., 2009; Rogier et
56 al., 2010) This preferential response to voices has not been clearly described in autistic people
57 with studies reporting contradictory results. No TVA was found in adults (Gervais et al., 2004)
58 on the autism spectrum due to a lack of activation in response to vocal sounds. Yet, normal
59 TVA activation was found in adults with autism and no Intellectual Disability (ID) (Schelinski
60 et al., 2016). In an EEG study, autistic children did not show a preferential response to vocal
61 sounds, but this mainly reflected an atypical processing of non-vocal sounds (Bidet-Caulet et
62 al., 2017). Cortical activations in response to speech sounds were also reported to be lower in

63 autistic children, especially in the inferior frontal gyrus (Lai et al., 2012; Sharda et al., 2015)
64 and in the left temporal cortex (Eyler et al., 2012). It appears that voice processing, and in
65 particular spoken voice processing may be different in autism, although the lack of consensus
66 could reflect the high heterogeneity observed in autism spectrum, at both individual and
67 population level (Latinus et al., 2019).

68 Like language, music carries emotions and is an integral part of everyday life. Music differs
69 mainly from language by its lack of semantic content and its acoustical structure (Leaver &
70 Rauschecker, 2010). The existence of brain regions specialized in music processing remains an
71 open question, with some studies reporting overlap of regions involved in music and voices
72 (Peretz et al., 2015) and others looking at impaired music processing suggesting it may be
73 relatively independent from language processing (Peretz, 2009).

74 Since the first behavioral descriptions of autism, music has a special status. A keen interest in
75 music, associated with equivalent or superior skills in music with respect to neurotypical
76 individuals has often been reported (Bonnell et al., 2003; Heaton et al., 1999; Mottron et al.,
77 2000; Wang et al., 2022). In a behavioral study, Boso et al. (2009) have shown that autistic
78 people share the same musical preferences as neurotypical individuals. In addition, cortical
79 activation in response to music seem to be preserved in ASD (Gebauer et al., 2014).

80 Music differs from environmental sounds, and vocal sounds by its acoustical structure. In
81 particular, harmonics-to-noise ratio (HNR) in musical sounds is on average higher than that of
82 human and animal vocalizations including songbirds and environmental sounds (Leaver &
83 Rauschecker, 2010).

84 The HNR is an important signal in auditory perception. Because the HNR of human and animal
85 vocalizations is higher than other natural sounds, it seems to be an important acoustical attribute
86 for vocal perception (Lewis et al., 2005, 2009). It has been shown that perceived vocal
87 attractiveness, which is positively correlated with HNR (Bruckert et al., 2010), modulates the

88 cortical activity, particularly in bilateral inferior prefrontal regions (Bestelmeyer et al., 2012).
89 In addition, a specific HNR-sensitive brain regions has been highlighted in the human auditory
90 cortex (Leaver & Rauschecker, 2010; Lewis et al., 2009). Therefore, HNR appears important
91 in voice perception and in sound pleasantness.

92 Within the vocal category, sung voices have a special status, compared with spoken voices:
93 they are closer to music, present less variability in fundamental frequency, and have a more
94 harmonic acoustical structure, as reflected by higher HNR (Sharda et al., 2015; Stegemöller et
95 al., 2008). Specific brain responses to sung music, located in middle and anterior STG, have
96 been identified in NT people in an functional Magnetic Resonance Imaging (fMRI) study
97 (Norman-Haignere et al., 2022). Activation in response to sung voices is reported to be similar
98 (Sharda et al., 2015) or increased (Lai et al., 2012) in autism. Whispered voices can be
99 considered as the other bound of the vocal category; they are characterized by low HNR, due
100 to the lack of vocal folds vibration.

101 HNR is an acoustic marker important for voice perception, but also associated with voice
102 attractiveness, and which varies between sung voices, music and spoken voices. HNR is a
103 measured of the noise within the stimulus itself, and as such can be considered as an exogenous
104 noise. Endogenous neural noise (Davis & Plaisted-Grant, 2015) has been highlighted as key
105 factor in ASD: some authors suggest that an enhanced endogenous neural noise level in ASD
106 sensory system (Simmons et al., 2009) may induce difficulties in sensory discrimination (Tang
107 et al., 2014) and prioritization of afferent signals. On the contrary, others suggest that a reduced
108 level of endogenous brain noise would enlighten an enhanced sensory detection and
109 discrimination in ASD (Davis & Plaisted-Grant, 2015). Concerning exogeneous noise, there is
110 few relevant literatures in the auditory modality; yet, in visual perception study, it is well
111 admitted that autistic persons process better avatars than real faces (Pino et al., 2021),
112 interestingly avatars are in general less noisy than real faces. This raises question on the role of

113 exogeneous noise, i.e., here HNR, in the perception of sounds by people on the autism spectrum.
114 To our knowledge, no studies have investigated auditory pleasantness in adults on the autism
115 spectrum; the literature focuses on the investigation of auditory preferences in children.
116 Behavioral studies have highlighted a preference for Child Directed Speech (CDS) to Adult
117 Directed Speech (Fernald, 1985) in NT children, even more pronounced for their mother's
118 speech (Klin, 1991, 1992), but no differences between sung and spoken voices (Blackstock,
119 1978). On the contrary, children on the autism spectrum do not prefer CDS (Paul et al., 2007),
120 and prefer non-vocal stimuli (Kuhl et al., 2005) or musical sounds (Blackstock, 1978). Using
121 an active task, it was shown that autistic children do not prefer their own mother's speech, but
122 prefer loud monotonous sound (hubbub), contrary to NT children (Klin, 1991, 1992). However,
123 as observed in NT children, autistic children show a preference for vocal prosodic sounds,
124 compared to vocal monotonous sounds and to mechanical prosodic and monotonous sounds
125 (Gilbertson et al., 2017). Finally, while NT children do not show preference between sung and
126 spoken voices, autistic children seem to prefer sung voices (Blackstock, 1978).

127 Thus, to our knowledge, no studies exist on direct auditory pleasantness assessment who
128 compare vocal and non-vocal stimuli preferences, with varying level of HNR.

129 The primary aim of this study was to evaluate subjective auditory preferences in ASD. Our
130 general hypothesis was that pleasantness judgements of people on the autism spectrum will
131 differ from those of NT people according to the social nature and the exogenous noise, e.g., the
132 HNR of the sounds. We expected that people on the autism spectrum would rate non-vocal
133 sounds as more pleasant than voices, contrarily to neuro-typical people (NT) who would give
134 higher pleasantness judgments to vocal sounds. We expected HNR to influence more
135 pleasantness judgements of both vocal and non-vocal sounds in autistic people than in NT
136 people. To probe this, we assessed auditory pleasantness using active behavioral ratings.

137

METHODS

138 This research was approved by: the Comité de Protection des Personnes EST I the 2017-04-20
139 (2017/23-ID RCB: 2017-A00756-47; PROSCEA) and the Comité d’Ethique pour les
140 Recherches Non Interventionnelles Tours-Poitiers-1 on 2017-12-02.

141 *Participants*

142 16 adults on the autism spectrum (6 women; mean age: 27.4 years old (± 6.7)) recruited from
143 the Centre de Ressources Autisme, Centre Val de Loire and the child psychiatry department of
144 Tours University Hospital participated in this study. The diagnosis of ASD was made by a
145 pluridisciplinary team of expert clinicians according to DSM-IV-TR/5 and the Autism
146 Diagnosis Interview-Revised (ADI-R), the Autism Diagnostic Observation Scale - second
147 edition (ADOS-2). 16 neuro-typical adults (6 women; mean age: 27.8 years old (± 6.3)) without
148 personal history of neurological or psychiatric disorders or early learning disabilities, were
149 matched in gender and age with people on the autism spectrum. The cognitive abilities of
150 individuals were assessed using the Wechsler Intelligence Scales adapted to the age of
151 individuals. All participants had normal hearing (direct audiometric subjective test for NT
152 participants; clinical reports from the medical team for autistic participants). All participants
153 were native speaker of French. Participants characteristics are summarized in table 1.

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163 **Table 1. Participants characteristics**

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	ASD		NT	
	F	M	F	M
Age (months)	n = 6	n = 10	n = 6	n = 10
$\mu (\pm \sigma)$	26.93 (\pm 5.71)	23.34 (\pm 9.57)	26.69 (\pm 5.19)	28.54 (\pm 7.11)
NVDQ	n = 4	n = 10	n = 4	n = 7
$\mu (\pm \sigma)$	104.5 (\pm 17.17)	101.8 (\pm 17.29)	121.88 (\pm 17.61)	124.43 (\pm 6.05)
VDQ	n = 4	n = 10	n = 4	n = 7
$\mu (\pm \sigma)$	107.5 (\pm 23.69)	109.6 (\pm 22.45)	102.5 (\pm 14.73)	108.57 (\pm 14.64)
AQ	n = 4	n = 6	n = 4	n = 7
$\mu (\pm \sigma)$	40 (\pm 2.83)	30.3 (\pm 6.83)	15.29 (\pm 5.96)	14.57 (\pm 6.95)
EQ	n = 4	n = 8	n = 4	n = 7
$\mu (\pm \sigma)$	16.5 (\pm 7.05)	23.88 (\pm 8.22)	44.29 (\pm 8.88)	39.43 (\pm 4.93)
ADOS – RRB	n = 4	n = 8	-	-
$\mu (\pm \sigma)$	3.25 (\pm 1.71)	1.63 (\pm 1.30)		
ADOS – SI	n = 4	n = 8	-	-
$\mu (\pm \sigma)$	9 (\pm 5.1)	8.38 (\pm 5.04)		
CARS	n = 5	n = 9	-	-
$\mu (\pm \sigma)$	26.25 (\pm 2.5)	26.43 (\pm 4.39)		

165 Note that the ADOS-SI scores is the mean of SI score for participants who were evaluated with ADOS2 and the
166 sum of communication and SI factors for those evaluated with ADOS1. Due to missing data, the identity and
167 number of participants included in each of these calculations are not identical. NVDQ = Non-verbal Development
168 Quotient, VDQ = Verbal Development Quotient, AQ = Autism Quotient, EQ = Empathy Quotient, ADOS SI =
169 Autism Diagnostic Observation Schedule – Social Interactions, ADOS RRB = Autism Diagnostic Observation
170 Schedule – Restrictive and Repetitive Behaviors, CARS = Childhood Autism Rating Scale.

171

172 *Stimuli*

173 The experimental material was composed of vocal and non-vocal sounds, with three conditions
174 of noise level per category: sung, spoken and whispered voices, and musical, animal and
175 environmental sounds (Figure 1). All sounds were natural sound recordings. The 3 HNR levels
176 (low/medium/high) were quite distinct ($F(2, 84) = 126.69, p < .001$), but equivalent across the
177 2 categories (vocal/non-vocal) ($F(1, 84) = 1.97, p = 0.02$). There was an interaction between
178 HNR level and category ($F(2, 84) = 9.36, p = < .001$), showing a higher HNR for music than

179 for sung voices and a smaller HNR for environmental sounds than whispered voices.

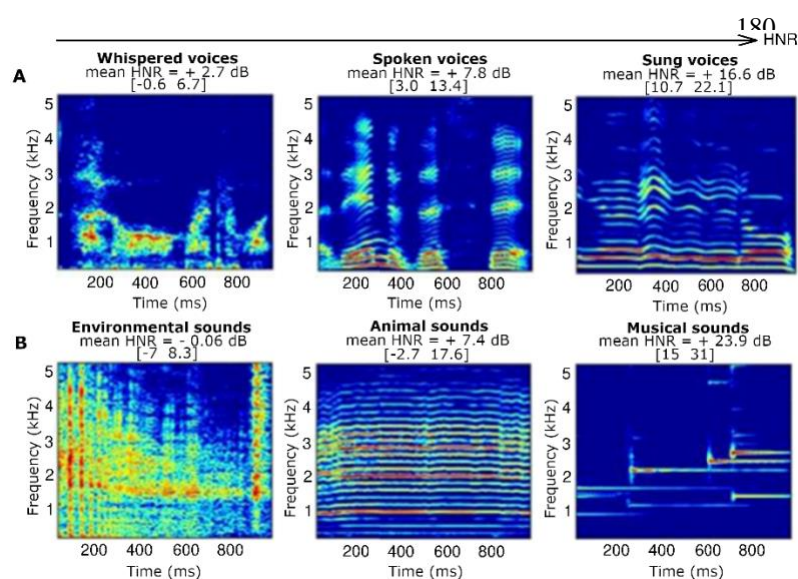


Fig. 1 Spectrograms of each six sounds conditions. A block is vocal sounds, B block is non-vocal sounds. Mean HNR values are means of all 15 sounds per condition. Images are spectrograms of one example of sound of this condition.

192 The 90 final stimuli were selected from a sample of 131 original sounds, previously evaluated
 193 in a pilot version of the study ran on 13 different NT adults (10 women; mean age: 22 years old
 194 (± 1.96)). In order to constitute six homogeneous sound categories, the final stimuli were
 195 selected to maximize intra-condition homogeneity in each condition, measured with the
 196 Cronbach's alpha on sound pleasantness judgements of participants (Nunnally & Bernstein,
 197 1994). At the end, there were 15 sounds per condition with inter-stimuli intra-condition
 198 reproducibility above 0.85 (Table 2).

199 **Table 2. Cronbach's alpha values for each sound category**

Cronbach's alpha values per conditions	
n=90	
Sung sounds	0.926
Spoken sounds	0.924
Whispered sounds	0.981
Musical sounds	0.919
Animal sounds	0.855
Environmental sounds	0.893

200 Vocal sounds were speech sounds produced by speakers of both genders, and of different
201 languages (german, english, spanish, galician, french, japanese and swedish) to reduce the
202 influence of semantic understanding on pleasantness judgements. Non-vocal sounds were from
203 different sources such as musical instruments (playing musical notes), animal calls and daily
204 environmental sounds (for example cars, ring tone, door, wind, rain).

205 All sounds were normalized in intensity. The mean duration of all sounds ($\pm \sigma$) was 839 ± 147
206 ms. In order to minimize clicks, a ramp of 5 % of the sounds durations was applied at the end
207 of each sound.

208 *Experimental design*

209 The sound pleasantness judgement task was run with the PsychToolbox within the MATLAB
210 environment (release 7.11.0.584). All participants performed the task on a laptop, in a sound-
211 attenuated room; sounds were presented through the laptop loudspeakers at a level comfortable
212 to the participant.

213 Participant listened to a sound (that could be freely replayed with the « play » button) and had
214 to evaluate the pleasantness of the sound using a visual analog scale, ranging from « not
215 pleasant at all » to « very pleasant». The next sound was played 2 seconds after validation of
216 their choice. They rated pleasantness on the 90 sounds presented in a random order. Task
217 duration varied across participants ranging from 11 to 18 minutes. For autistic participants with
218 ID the experimenter recorded their response without influencing their judgment and emoticons
219 were presented to facilitate the comprehension of the task.

220 *Data analysis*

221 The data analyzed here are the raw numerical data, corresponding to pleasantness ratings of
222 each sound, ranging from 0 « not pleasant at all / very unpleasant » to 1 « very pleasant». The
223 data were not normalized so as to keep the rating range of the participant as this could be
224 influenced by diagnosis.

225 Statistical analysis and graphics were performed with R (v.4.1.1 - R Core Team, 2018) and R
226 Studio (v. 1.4.1717 - RStudio Team, 2020) using the following packages: plotrix (Lemon,
227 2006), ggplot2 (Wickham, 2016), lsmeans (Lenth, 2016), lmerTest (Kuznetsova et al., 2017),
228 lme4 (Bates et al., 2015), tidyverse (Wickham et al., 2019), lattice (Sarkar, 2008), rstatix
229 (Kassambara, 2021), ggpubr (Kassambara, 2020), ggcorrplot (Kassambara, 2019), corrplot
230 (Wei & Simko, 2021), viridis (Garnier et al., 2021), hrbthemes (Rudis, 2020) and gridExtra
231 (Auguie, 2017). The figures were created with the following software: R (v.4.1.1), R Studio (v.
232 1.4.1717) and GIMP (v.2.10.22).

233 *Correlational analysis*

234 Intra-group correlations were estimated by correlating individual ratings of participants with
235 one another within each diagnostic group (ASD or NT). Correlation between pleasantness and
236 HNR were performed using the mean pleasantness ratings of each sound per group.

237 Significance of correlations was determined with bootstrap method (10 000 bootstrap), by
238 creating a theoretical distribution of Spearman's coefficient under the null hypothesis (H0) of a
239 lack of correlation, obtained by sampling with replacement one of the value of a pair (e.g.,
240 pleasantness in pleasantness/HNR correlations, one participant in between participants
241 correlations). The correlations' 95% confidence interval (CI95%) was estimated under the
242 alternative hypothesis (H1), through the creation of a theoretical distribution of Spearman's
243 coefficient obtained by sampling the pairs with replacement. Statistical analysis of the
244 difference between correlations was performed by measuring the real difference in Spearman's
245 coefficient, then calculating theoretical distribution of differences under H0, using permutation
246 tests (10 000 permutations).

247 *Statistical analysis*

248 Linear mixed effects models were used to better consider inter-participants and inter-stimuli
249 variability. Initially two models were tested, both had pleasantness ratings as the dependent

250 variable and group, sound category and HNR level and their interactions as fixed effects (group
251 (2 levels: ASD/NT) x category (2 levels: vocal/non-vocal) x HNR (3 levels:
252 low/medium/high)). In the first one (M1), random effects for a particular subject were the
253 deviations in intercept of that subject's pleasantness rating from the population. In the second
254 one (M2), in addition to subject's random effects, random effects for a particular sound were
255 the deviations in intercept of that sound's pleasantness rating from the complete sample of
256 sounds. Comparisons of the two models using an ANOVA ('stats' package - R Core Team,
257 2018) revealed that the model with both sounds and subjects as random effects better explained
258 the data (AIC_M1 = -1139.9; AIC_M2 = -1342; Chi2 = 204.14; $p < 0.001$).

259 Model 2 was then optimized using the "step" function ('stats' package - R Core Team, 2018),
260 revealing that the model that best explained our data was the following one (final model):

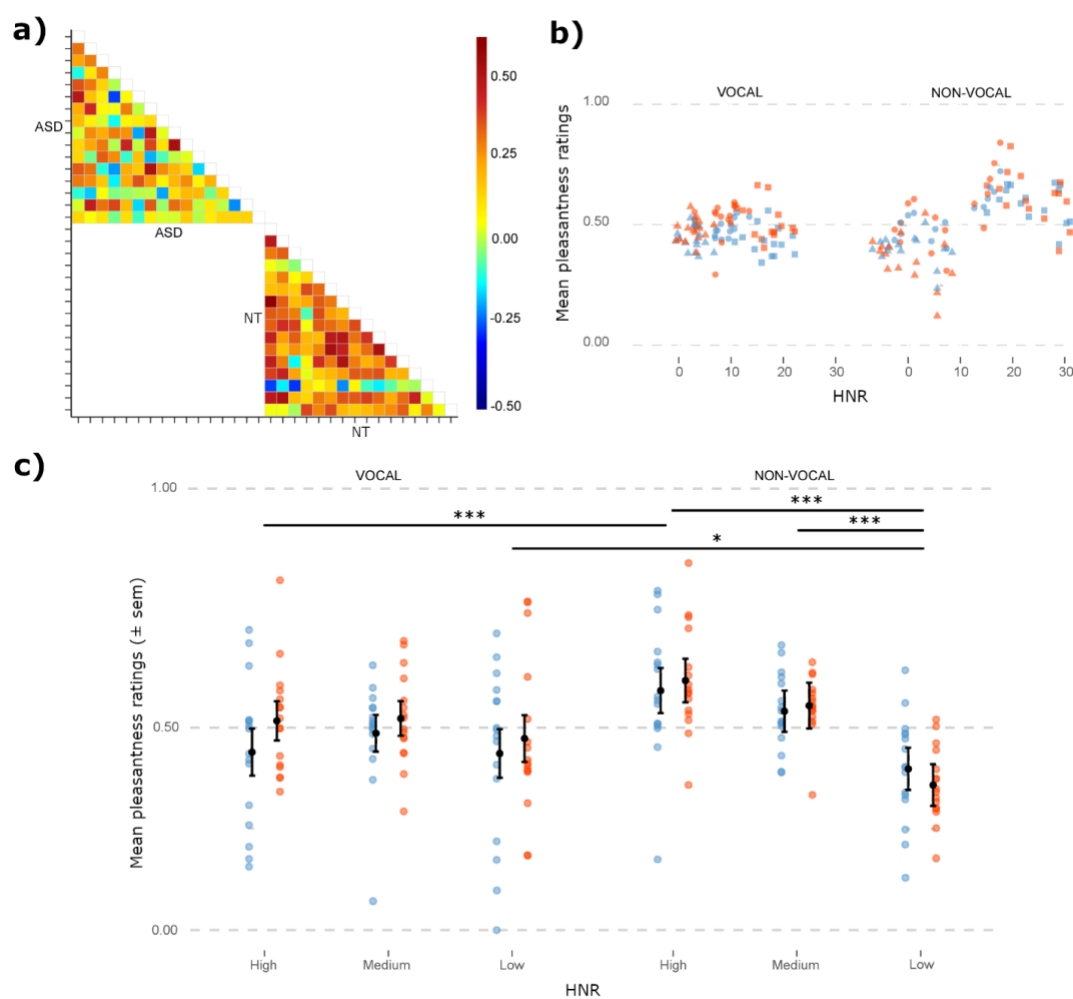
261 Ratings ~ Group + Category + HNR + (1 | Subjects) + (1 | Sounds) + Group:Category +
262 Group:HNR + Category:HNR. Model optimization resulted in the three-way interaction not
263 being tested.

264 The anova comparing M2 and the final model revealed no significant difference between the two
265 models (AIC_M2 = -1342; AIC_fm = -1343.4; Chi2 = 2.63; $p = 0.2679$), therefore we choose
266 the final model as it had a smaller number of parameters estimates (13 vs. 15 in M2) according
267 to the Principle of Parsimony (Vandekerckhove et al., 2015).

268 *RESULTS*

269 *Correlations*

270 Intra-group correlations revealed a larger group-variability ($T(238) = -4.80$, $p < .001$), indexed
271 by a lower mean Spearman rho in the ASD group [mean $\rho (\pm \sigma) = 0.18 (\pm 0.30)$], than in the
272 NT group [mean $\rho (\pm \sigma) = 0.30 (\pm 0.22)$]. Sounds pleasantness ratings were more similar across
273 NT participants than across autistic participants (Figure 2-a).



274

275 **Fig. 2 a)** Correlation coefficient of each subject with others subjects of his group. Left upper triangle represent
 276 correlation between ASD subjects; right lower triangle represent correlation between NT subjects.

277 **b)** Points cloud illustrating pleasantness ratings of ASD and NT group by HNR – triangles represent low HNR
 278 level, circles represent medium HNR level and squares represent high HNR level. ASD participants are represented
 279 in blue and NT participants are representing in orange. **c)** Point graph illustrating mean pleasantness ratings (\pm
 280 sem) of ASD and NT participants and HNR levels – ASD participants are blue points, NT participants are orange
 281 point. Each color point represents the mean ratings for one subject for one HNR condition (15 sounds). Black
 282 points represent mean pleasantness ratings of all the 16 participants for one HNR condition and black line represent
 283 the error-bar (\pm sem).

284

285 Analysis of the correlations between HNR and pleasantness ratings in vocal sounds showed no

286 significant correlation for either group: ASD group [ρ [IC95%] = -0.08 [-0.38 0.24]; $p = 0.60$],

287 NT group [ρ [IC95%] = 0.17 [-0.12 0.45]; $p = 0.27$], and no difference between the groups [ρ

288 difference [IC95%] = -0.25 [-0.46 -0.03]; $p = 0.10$]. For non-vocal sounds, pleasantness ratings

289 was positively correlated with HNR for both the ASD group [ρ [IC95%] = 0.65 [-0.44 0.22]; p

290 $< .001$] and NT group [ρ [IC95%] = 0.57 [-0.27 0.32]; $p < .001$], and there was no significant

291 between-group differences [ρ difference [IC95%] = 0.08 [-0.38 0.09]; $p = 0.11$]. The higher the
292 HNR is, the more pleasant the sounds are rated. HNR explains 42.12 % of the variance of ASD
293 participants for the non-vocal category, and 32.27 % of the variance of NT participants (Figure
294 2-b).

295 *Linear Mixed Model*

296 The chosen model included group, HNR levels and category (vocal/non-vocal) and category by
297 group, category by HNR and group by HNR interactions as fixed effects, and subjects and
298 sounds as the only intercept random effects. Analysis of the model outputs revealed no effect
299 of group on pleasantness ratings ($F(1, 31.97) = 0.66, p = 0.42$), but significant main effects of
300 HNR ($F(2, 89.38) = 25.62, p < .001$) and category ($F(1, 89.38) = 3.95, p < .05$) (Figure 2-c).

301 A significant category by HNR interaction was found ($F(2, 89.38) = 14.34, p < .001$), revealing
302 that HNR level influences differently pleasantness ratings of the two sound categories (vocal
303 and non-vocal): participants rated sounds with a high HNR as more pleasant for non-vocal
304 sounds, while for vocal sounds spoken voices were the most pleasant. Planned pairwise
305 comparisons with adjusted p values (for 9 comparisons) were performed to specify this
306 interaction. Mean pleasantness ratings were lower for non-vocal low HNR (environmental
307 sounds) than for non-vocal medium HNR (animal sounds) ($p < .001$), and for non-vocal high
308 HNR (music) ($p < .001$), which did not differ. Mean pleasantness ratings for non-vocal high
309 HNR (music) were significantly higher than those for vocal high HNR (sung voices) ($p < .001$);
310 the opposite was true for low HNR sounds: ratings were higher in the vocal than in the non-
311 vocal category ($p = 0.049$). No other planned comparisons were significant.

312 A significant group by category interaction ($F(1, 2758.92) = 13.80, p < .001$) revealed that while
313 no difference in mean ratings was observed between category in the NT group, participants on
314 the autism spectrum rated vocal sounds as less pleasant than non-vocal sounds (corrected p
315 values for 4 comparisons $< .05$).

316 Finally, a significant group by HNR interaction ($F(2, 2758.92) = 5.01, p < .01$) highlighted that
317 HNR level influenced differently pleasantness ratings between ASD and NT participants.
318 Pairwise comparisons with adjusted p values (for 9 comparisons) were performed to specify
319 this interaction. ASD mean pleasantness ratings of low HNR stimuli were significantly lower
320 than those of high ($p < .001$), and medium HNR ($p < .001$), which did not differ. In the NT group,
321 mean pleasantness ratings for low HNR were significantly lower than for high ($p < .001$) and
322 medium HNR ($p < .001$), which did not differ. Note that within an HNR level there was no
323 group difference (all $p > 0.05$), nonetheless, it appears that NT participants tended to rate as
324 more pleasant stimuli with a high HNR relative to ASD participants, while ASD participants
325 rated more pleasant stimuli with low HNR relative to NT participants (Figure 2c).

326 *DISCUSSION*

327 We aimed to evaluate auditory pleasantness in autism spectrum disorder. Based on literature
328 reports of a keen interest in, and intact processing of, music (Bonnell et al., 2003; Heaton et al.,
329 1999; Mottron et al., 2000; Wang et al., 2022), and intact processing of sung voices (Lai et al.,
330 2012; Sharda et al., 2015) in autism, we expected HNR to play a crucial role in the perception
331 of pleasantness in ASD. Our main hypothesis was that pleasantness judgements of people on
332 the autism spectrum would differ from NT people according to the social nature (from a human
333 being, e.g., the voice) of the sounds and its acoustical noise level. To the best of our knowledge,
334 this is the first study to empirically assess auditory pleasantness in ASD. Using a pleasantness
335 rating task, we showed that autistic participants judge non-vocal sounds more pleasant than
336 vocal sounds. Both groups of participants were more sensitive to noise level in non-vocal
337 sounds than in vocal sounds. Nonetheless, NT participants tended to consider as more pleasant
338 sounds with a more regular structure than did the participants on the autism spectrum.
339 Correlations between participants' pleasantness judgements were higher within the NT group
340 than within the autistic group, consistent with previous reports highlighting the higher

341 variability of response in people on the autism spectrum in neuroimaging studies (Hahamy et
342 al., 2015; Latinus et al., 2019; Milne, 2011). This shows that even on a relatively simple
343 behavioral task, response of autistic participants differs greatly and caution should be taken to
344 interpret data. To consider participant variability we choose to analyze data with a linear mixed
345 model with subject and sounds as random effects.

346 This study confirmed empirically the larger aversion for vocal sounds than non-vocal sounds
347 in autism; however, we failed to show that NT participants found vocal sounds as more pleasant
348 than non-vocal sounds. These results are consistent with clinical observation of an avoidance
349 of vocal stimulation in autism (American Psychiatric Association, 2013). Yet, these data do not
350 allow demonstrating that the lack of preference for vocal sounds in autism was driven by an
351 averaged lower HNR in vocal sounds. In NT adults, we failed to show a relationship between
352 HNR value and sounds pleasantness in vocal sounds, contrarily to what was shown using
353 attractiveness ratings (Bestelmeyer et al., 2012; Bruckert et al., 2010), suggesting that
354 attractiveness and pleasantness are not rooted in the same processes. In addition, participants
355 rated pleasantness in sounds from different categories and other sounds could have influence
356 judgements by creating a contextual norm. Both groups rated as more pleasant musical sounds
357 than the other sound categories, consistent with previous results (Boso et al., 2009).

358 Previous neuroimaging studies on voice perception in ASD have reported contradictory results.
359 In one study with adults on the autism spectrum and associated intellectual disability it was
360 shown that autistic adults did not show a preferential response to voices, due to a decrease
361 response to voices (Gervais et al., 2004). On the other hand, in a study with a larger sample of
362 adults without ID, a normal response to vocal sounds was found (Schelinski et al., 2016). In
363 addition, in a study in children on the autism spectrum, it was shown that a subset of autistic
364 children presented an altered response to non-vocal sounds (Bidet-Caulet et al., 2017; Latinus
365 et al., 2019). It was suggested that this may reflect the atypical development of filters that allows

366 optimizing voice perception in neurotypical development (Bidet-Caulet et al., 2017). HNR is
367 one of the secondary features extracted from vocal sounds (Leaver & Rauschecker, 2010; Lewis
368 et al., 2009), based on the integration of information extracted at the first level of processing.
369 In our study, we mainly included adults on the autism spectrum without ID, while the subset of
370 children showing impaired voice processing appears to be the one with lower verbal IQ (Latinus
371 et al., 2019). Therefore, in our population of autistic adults the processing of HNR remains
372 intact, and these participants may be less sensitive to noise in auditory stimulation as could have
373 been expected. This could suggest that in the current sample of participants the first steps of
374 sound processing, that consist of extracting HNR information, is intact. The aversion for vocal
375 sounds reported in clinical observation likely reflects processes at later steps of voice
376 perception, such as social (Martineau et al., 2011) or cognitive (Gebauer et al., 2014).

377 A hypothesis was that the development of voice perception ability depends on the functioning
378 of different steps in voice perception and impaired HNR processing could therefore influence
379 voice encoding.

380 In our group of autistic adults, mainly with no ID (only two participants), we found evidence
381 that they judged vocal sounds and non-vocal sounds pleasantness differently, suggesting that
382 these two sounds category are not equivalent in ASD. Although HNR influence pleasantness
383 ratings, it was similar across the two groups suggesting that HNR alone does not explain the
384 difference in sound appreciation. Note that contrarily to what we expected adults on the autism
385 spectrum did not consider as more pleasant sounds with a high HNR. Note that part of our
386 results could be explained by a confound between HNR levels and sound types as HNR
387 variability was obtained using different sound categories that may have different impacts on
388 autistic and NT individuals.

389 *Limitations*

390 Our task was an active judgment task, which limited the inclusion participants with associated

391 intellectual disability (only two participants). This could be an important features of voice
392 perception as previous studies have described a subset of children showing impaired voice
393 perception, but those were characterized by low verbal IQ; a subsample of participants not
394 really present in the current study. It would be interesting to evaluate auditory pleasantness, in
395 linked with HNR level, using passive task such as preferential looking paradigm.

396 *Conclusion*

397 Autistic adults judged non-vocal sounds more pleasant, confirming empirically clinical
398 observation. Our results highlighted a dichotomy in the pleasantness judgements of vocal and
399 non-vocal category, which was dependent on HNR level but group independent. Therefore, it
400 seems that in our group of autistic adults, HNR is not the acoustical features that explains
401 atypical auditory preference in ASD.

402

403 *Ethics approval*

404 This research was approved by: the Comité de Protection des Personnes EST I the 2017-04-20
405 (2017/23-ID RCB: 2017-A00756-47; PROSCEA) and the Comité d’Ethique pour les
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407

408 *Statement and Declarations*

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411

412 *Authors contribution*

413 Lisa Michel and Marianne Latinus wrote the manuscript. Lisa Michel and Marianne Latinus
414 conceived, administered, analyzed and interpreted the data. Camille Ricou contributed to the
415 theoretical statistical review. Frédérique Bonnet-Brilhault and Emmanuelle Houy-Durand

416 contribute to the recruitment of participants and data interpretation. All authors read and
417 approved the final manuscript.

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421 *References*

- 422 American Psychiatric Association (Ed.). (2013). *Diagnostic and statistical manual of mental disorders: DSM-5*
 423 (5th ed). American Psychiatric Association.
- 424 Auguie, B. (2017). *gridExtra: Miscellaneous Functions for “Grid” Graphics*. [https://CRAN.R-](https://CRAN.R-project.org/package=gridExtra)
 425 [project.org/package=gridExtra](https://CRAN.R-project.org/package=gridExtra)
- 426 Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal*
 427 *of Statistical Software*, 67(1). <https://doi.org/10.18637/jss.v067.i01>
- 428 Belin, P., Bestelmeyer, P. E. G., Latinus, M., & Watson, R. (2011). Understanding voice perception. *British*
 429 *Journal of Psychology (London, England: 1953)*, 102(4), 711–725. <https://doi.org/10.1111/j.2044->
 430 [8295.2011.02041.x](https://doi.org/10.1111/j.2044-8295.2011.02041.x)
- 431 Belin, P., Fecteau, S., & Bédard, C. (2004). Thinking the voice: Neural correlates of voice perception. *Trends in*
 432 *Cognitive Sciences*, 8(3), 129–135. <https://doi.org/10.1016/j.tics.2004.01.008>
- 433 Belin, P., Zatorre, R. J., Lafaille, P., Ahad, P., & Pike, B. (2000). Voice-selective areas in human auditory cortex.
 434 *Nature*, 403(6767), 309–312. <https://doi.org/10.1038/35002078>
- 435 Bestelmeyer, P. E. G., Latinus, M., Bruckert, L., Rouger, J., Crabbe, F., & Belin, P. (2012). Implicitly perceived
 436 vocal attractiveness modulates prefrontal cortex activity. *Cerebral Cortex (New York, N.Y.: 1991)*, 22(6),
 437 1263–1270. <https://doi.org/10.1093/cercor/bhr204>
- 438 Bidet-Caulet, A., Latinus, M., Roux, S., Malvy, J., Bonnet-Brilhault, F., & Bruneau, N. (2017). Atypical sound
 439 discrimination in children with ASD as indicated by cortical ERPs. *Journal of Neurodevelopmental*
 440 *Disorders*, 9, 13. <https://doi.org/10.1186/s11689-017-9194-9>
- 441 Blackstock, E. G. (1978). Cerebral asymmetry and the development of early infantile autism. *Journal of Autism*
 442 *and Childhood Schizophrenia*, 8(3), 339–353. <https://doi.org/10.1007/BF01539636>
- 443 Bonnel, A., Mottron, L., Peretz, I., Trudel, M., Gallun, E., & Bonnel, A.-M. (2003). Enhanced pitch sensitivity in
 444 individuals with autism: A signal detection analysis. *Journal of Cognitive Neuroscience*, 15(2), 226–235.
 445 <https://doi.org/10.1162/089892903321208169>
- 446 Boso, M., Comelli, M., Vecchi, T., Barale, F., & Politi, P. (2009). Exploring Musical Taste in Severely Autistic
 447 Subjects. *Annals of the New York Academy of Sciences*, 1169(1), 332–335. <https://doi.org/10.1111/j.1749->
 448 [6632.2009.04853.x](https://doi.org/10.1111/j.1749-6632.2009.04853.x)
- 449 Bottema-Beutel, K., Kapp, S. K., Lester, J. N., Sasson, N. J., & Hand, B. N. (2021). Avoiding Ableist Language:
 450 Suggestions for Autism Researchers. *Autism in Adulthood*, 3(1), 18–29.

- 451 <https://doi.org/10.1089/aut.2020.0014>
- 452 Bruckert, L., Bestelmeyer, P., Latinus, M., Rouger, J., Charest, I., Rousselet, G. A., Kawahara, H., & Belin, P.
453 (2010). Vocal attractiveness increases by averaging. *Current Biology: CB*, 20(2), 116–120.
454 <https://doi.org/10.1016/j.cub.2009.11.034>
- 455 Capilla, A., Belin, P., & Gross, J. (2013). The Early Spatio-Temporal Correlates and Task Independence of
456 Cerebral Voice Processing Studied with MEG. *Cerebral Cortex*, 23(6), 1388–1395.
457 <https://doi.org/10.1093/cercor/bhs119>
- 458 Charest, I., Pernet, C. R., Rousselet, G. A., Quiñones, I., Latinus, M., Fillion-Bilodeau, S., Chartrand, J.-P., &
459 Belin, P. (2009). Electrophysiological evidence for an early processing of human voices. *BMC*
460 *Neuroscience*, 10, 127. <https://doi.org/10.1186/1471-2202-10-127>
- 461 Davis, G., & Plaisted-Grant, K. (2015). Low endogenous neural noise in autism. *Autism*, 19(3), 351–362.
462 <https://doi.org/10.1177/1362361314552198>
- 463 Eyster, L. T., Pierce, K., & Courchesne, E. (2012). A failure of left temporal cortex to specialize for language is an
464 early emerging and fundamental property of autism. *Brain*, 135(3), 949–960.
465 <https://doi.org/10.1093/brain/awr364>
- 466 Fernald, A. (1985). Four-month-old infants prefer to listen to motherese. *Infant Behavior and Development*, 8(2),
467 181–195. [https://doi.org/10.1016/S0163-6383\(85\)80005-9](https://doi.org/10.1016/S0163-6383(85)80005-9)
- 468 Garnier, S., Ross, N., Rudis, B., Camargo, A. P., Scanini, M., & Scherer, C. (2021). *Viridis—Colorblind-Friendly*
469 *Color Maps for R*. <https://sjmgarnier.github.io/viridis/>
- 470 Gebauer, L., Skewes, J., Westphael, G., Heaton, P., & Vuust, P. (2014). Intact brain processing of musical
471 emotions in autism spectrum disorder, but more cognitive load and arousal in happy vs. Sad music.
472 *Frontiers in Neuroscience*, 8. <https://doi.org/10.3389/fnins.2014.00192>
- 473 Gervais, H., Belin, P., Boddaert, N., Leboyer, M., Coez, A., Sfaello, I., Barthélémy, C., Brunelle, F., Samson, Y.,
474 & Zilbovicius, M. (2004). Abnormal cortical voice processing in autism. *Nature Neuroscience*, 7(8), 801–
475 802. <https://doi.org/10.1038/nn1291>
- 476 Gilbertson, L. R., Lutfi, R. A., & Ellis Weismer, S. (2017). Auditory preference of children with autism spectrum
477 disorders. *Cognitive Processing*, 18(2), 205–209. <https://doi.org/10.1007/s10339-016-0787-0>
- 478 Hahamy, A., Behrmann, M., & Malach, R. (2015). The idiosyncratic brain: Distortion of spontaneous connectivity
479 patterns in autism spectrum disorder. *Nature Neuroscience*, 18(2), 302–309.
480 <https://doi.org/10.1038/nn.3919>

- 481 Heaton, P., Pring, L., & Hermelin, B. (1999). A pseudo-savant: A case of exceptional musical splinter skills.
482 *Neurocase*, 5(6), 503–509. <https://doi.org/10.1080/13554799908402745>
- 483 Kanner, L. (1943). Autistic disturbances of affectiv contact. *Nervous Child*, 2, 217–250.
- 484 Kassambara, A. (2019). *ggcorrplot: Visualization of a Correlation Matrix using “ggplot2.”* [https://CRAN.R-](https://CRAN.R-project.org/package=ggcorrplot)
485 [project.org/package=ggcorrplot](https://CRAN.R-project.org/package=ggcorrplot)
- 486 Kassambara, A. (2020). *ggpubr: “ggplot2” Based Publication Ready Plots.* [https://CRAN.R-](https://CRAN.R-project.org/package=ggpubr)
487 [project.org/package=ggpubr](https://CRAN.R-project.org/package=ggpubr)
- 488 Kassambara, A. (2021). *rstatix: Pipe-Friendly Framework for Basic Statistical Tests.* [https://CRAN.R-](https://CRAN.R-project.org/package=rstatix)
489 [project.org/package=rstatix](https://CRAN.R-project.org/package=rstatix)
- 490 Klin. (1991). Young autistic children’s listening preferences in regard to speech: A possible characterization of
491 the symptom of social withdrawal. *Journal of Autism and Developmental Disorders*, 21(1), 29–42.
492 <https://doi.org/10.1007/BF02206995>
- 493 Klin. (1992). Listening preferences in regard to speech in four children with developmental disabilities. *Journal*
494 *of Child Psychology and Psychiatry, and Allied Disciplines*, 33(4), 4.
- 495 Kuhl, P. K., Coffey-Corina, S., Padden, D., & Dawson, G. (2005). Links between social and linguistic processing
496 of speech in preschool children with autism: Behavioral and electrophysiological measures.
497 *Developmental Science*, 8(1), F1–F12. <https://doi.org/10.1111/j.1467-7687.2004.00384.x>
- 498 Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest Package: Tests in Linear Mixed Effects
499 Models. *Journal of Statistical Software*, 82(13). <https://doi.org/10.18637/jss.v082.i13>
- 500 Lai, G., Pantazatos, S. P., Schneider, H., & Hirsch, J. (2012). Neural systems for speech and song in autism. *Brain*,
501 135(3), 961–975. <https://doi.org/10.1093/brain/awr335>
- 502 Latinus, M., Mofid, Y., Kovarski, K., Charpentier, J., Batty, M., & Bonnet-Brilhault, F. (2019). Atypical Sound
503 Perception in ASD Explained by Inter-Trial (In)consistency in EEG. *Frontiers in Psychology*, 10, 1177.
504 <https://doi.org/10.3389/fpsyg.2019.01177>
- 505 Leaver, A. M., & Rauschecker, J. P. (2010). Cortical Representation of Natural Complex Sounds: Effects of
506 Acoustic Features and Auditory Object Category. *Journal of Neuroscience*, 30(22), 7604–7612.
507 <https://doi.org/10.1523/JNEUROSCI.0296-10.2010>
- 508 Lemon, J. (2006). Plotrix: A package in the red light district of R. *R-News*, 6(4), 8–12.
- 509 Lenth, R. V. (2016). Least-Squares Means: The R Package lsmeans. *Journal of Statistical Software*, 69(1).
510 <https://doi.org/10.18637/jss.v069.i01>

- 511 Lewis, J. W., Brefczynski, J. A., Phinney, R. E., Janik, J. J., & DeYoe, E. A. (2005). Distinct Cortical Pathways
512 for Processing Tool versus Animal Sounds. *Journal of Neuroscience*, *25*(21), 5148–5158.
513 <https://doi.org/10.1523/JNEUROSCI.0419-05.2005>
- 514 Lewis, J. W., Talkington, W. J., Walker, N. A., Spirou, G. A., Jajosky, A., Frum, C., & Brefczynski-Lewis, J. A.
515 (2009). Human Cortical Organization for Processing Vocalizations Indicates Representation of Harmonic
516 Structure as a Signal Attribute. *Journal of Neuroscience*, *29*(7), 2283–2296.
517 <https://doi.org/10.1523/JNEUROSCI.4145-08.2009>
- 518 Martineau, J., Hernandez, N., Hiebel, L., Roché, L., Metzger, A., & Bonnet-Brilhault, F. (2011). Can pupil size
519 and pupil responses during visual scanning contribute to the diagnosis of autism spectrum disorder in
520 children? *Journal of Psychiatric Research*, *45*(8), 1077–1082.
521 <https://doi.org/10.1016/j.jpsychires.2011.01.008>
- 522 Milne, E. (2011). Increased intra-participant variability in children with autistic spectrum disorders: Evidence from
523 single-trial analysis of evoked EEG. *Frontiers in Psychology*, *2*, 51.
524 <https://doi.org/10.3389/fpsyg.2011.00051>
- 525 Mottron, L., Peretz, I., & Menard, E. (2000). Local and Global Processing of Music in High-functioning Persons
526 with Autism: Beyond Central Coherence? *Journal of Child Psychology and Psychiatry*, *41*(8), 1057–
527 1065. <https://doi.org/10.1111/1469-7610.00693>
- 528 Norman-Haignere, S. V., Feather, J., Boebinger, D., Brunner, P., Ritaccio, A., McDermott, J. H., Schalk, G., &
529 Kanwisher, N. (2022). A neural population selective for song in human auditory cortex. *Current Biology*,
530 *32*(7), 1470-1484.e12. <https://doi.org/10.1016/j.cub.2022.01.069>
- 531 Nunnally, J. C., & Bernstein, I. H. (1994). Elements of statistical description and estimation. In *Psychometric*
532 *Theory*. McGraw Hill: New York.
- 533 Paul, R., Chawarska, K., Fowler, C., Cicchetti, D., & Volkmar, F. (2007). “Listen my children and you shall hear”:
534 Auditory preferences in toddlers with autism spectrum disorders. *Journal of Speech, Language, and*
535 *Hearing Research: JSLHR*, *50*(5), 1350–1364. [https://doi.org/10.1044/1092-4388\(2007/094\)](https://doi.org/10.1044/1092-4388(2007/094))
- 536 Peretz, I. (2009). Music, Language and Modularity Framed in Action. *Psychologica Belgica*, *49*(2–3), 157.
537 <https://doi.org/10.5334/pb-49-2-3-157>
- 538 Peretz, I., Vuvan, D., Lagrois, M.-É., & Armony, J. L. (2015). Neural overlap in processing music and speech.
539 *Philosophical Transactions of the Royal Society B: Biological Sciences*, *370*(1664), 20140090.
540 <https://doi.org/10.1098/rstb.2014.0090>

- 541 Pino, M. C., Vagnetti, R., Valenti, M., & Mazza, M. (2021). Comparing virtual vs real faces expressing emotions
542 in children with autism: An eye-tracking study. *Education and Information Technologies*, 26(5), 5717–
543 5732. <https://doi.org/10.1007/s10639-021-10552-w>
- 544 R Core Team. (2018). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical
545 Computing. <https://www.R-project.org/>
- 546 Rogier, O., Roux, S., Belin, P., Bonnet-Brilhault, F., & Bruneau, N. (2010). An electrophysiological correlate of
547 voice processing in 4- to 5-year-old children. *International Journal of Psychophysiology: Official Journal*
548 *of the International Organization of Psychophysiology*, 75(1), 44–47.
549 <https://doi.org/10.1016/j.ijpsycho.2009.10.013>
- 550 RStudio Team. (2020). *RStudio: Integrated Development Environment for R*. RStudio, PBC.
551 <http://www.rstudio.com/>
- 552 Rudis, B. (2020). *hrbrthemes: Additional Themes, Theme Components and Utilities for “ggplot2.”*
553 <https://CRAN.R-project.org/package=hrbrthemes>
- 554 Rutherford, M. D., Baron-Cohen, S., & Wheelwright, S. (2002). Reading the Mind in the Voice: A Study with
555 Normal Adults and Adults with Asperger Syndrome and High Functioning Autism. *Journal of Autism*
556 *and Developmental Disorders*, 32(3), 189–194. <https://doi.org/10.1023/A:1015497629971>
- 557 Sarkar, D. (2008). *Lattice: Multivariate data visualization with R*. Springer.
- 558 Schelinski, S., Borowiak, K., & von Kriegstein, K. (2016). Temporal voice areas exist in autism spectrum disorder
559 but are dysfunctional for voice identity recognition. *Social Cognitive and Affective Neuroscience*, 11(11),
560 1812–1822. <https://doi.org/10.1093/scan/nsw089>
- 561 Sharda, M., Midha, R., Malik, S., Mukerji, S., & Singh, N. C. (2015). Fronto-temporal connectivity is preserved
562 during sung but not spoken word listening, across the autism spectrum. *Autism Research: Official Journal*
563 *of the International Society for Autism Research*, 8(2), 174–186. <https://doi.org/10.1002/aur.1437>
- 564 Simmons, D. R., Robertson, A. E., McKay, L. S., Toal, E., McAleer, P., & Pollick, F. E. (2009). Vision in autism
565 spectrum disorders. *Vision Research*, 49(22), 2705–2739. <https://doi.org/10.1016/j.visres.2009.08.005>
- 566 Stegemöller, E. L., Skoe, E., Nicol, T., Warrier, C. M., & Kraus, N. (2008). Music Training and Vocal Production
567 of Speech and Song. *Music Perception*, 25(5), 419–428. <https://doi.org/10.1525/mp.2008.25.5.419>
- 568 Tang, G., Gudsnuk, K., Kuo, S.-H., Cotrina, M. L., Rosoklija, G., Sosunov, A., Sonders, M. S., Kanter, E.,
569 Castagna, C., Yamamoto, A., Yue, Z., Arancio, O., Peterson, B. S., Champagne, F., Dwork, A. J.,
570 Goldman, J., & Sulzer, D. (2014). Loss of mTOR-Dependent Macroautophagy Causes Autistic-like

- 571 Synaptic Pruning Deficits. *Neuron*, 83(5), 1131–1143. <https://doi.org/10.1016/j.neuron.2014.07.040>
- 572 Vandekerckhove, J., Matzke, D., & Wagenmakers, E. J. (2015). Model comparison and the principle of parsimony.
573 In *Oxford handbook of computational and mathematical psychology* (Busemeyer, J., Townsend, J.,
574 Wang, Z. J., Eidels, A.). Oxford University Press.
- 575 Wang, L., Ong, J. H., Ponsot, E., Hou, Q., Jiang, C., & Liu, F. (2022). Mental representations of speech and
576 musical pitch contours reveal a diversity of profiles in autism spectrum disorder. *Autism*,
577 13623613221111208. <https://doi.org/10.1177/13623613221111207>
- 578 Wei, T., & Simko, V. (2021). *R package “corrplot”: Visualization of a Correlation Matrix*.
579 <https://github.com/taiyun/corrplot>
- 580 Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis* (Springer-Verlag New York).
581 <https://ggplot2.tidyverse.org>
- 582 Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry,
583 L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel,
584 D., Spinu, V., ... Yutani, H. (2019). Welcome to the Tidyverse. *Journal of Open Source Software*, 4(43),
585 1686. <https://doi.org/10.21105/joss.01686>
- 586