Model-based frontal cortex analysis reveals origins of human non-verbal communication

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Abstract

The ability to process verbal language seems unique to humans and relies not only on semantics but on other forms of communication such as affective vocalisations, that we share with other primate species—particularly great apes (*Hominidae*). To better understand these processes at the behavioural and brain level, we asked human participants to categorize vocalizations of four primate species including human, great apes (chimpanzee and bonobo), and monkey (rhesus macaque) during MRI acquisition. Classification was above chance level for all species but bonobo vocalizations. Imaging analyses were computed using a participant-specific, trial-by-trial fitted probability categorization value in a model-based style of data analysis. Model-based analyses revealed the implication of the bilateral orbitofrontal cortex and inferior frontal gyrus *pars triangularis* (IFG_{tri}) respectively correlating and anti-correlating with the fitted probability of accurate species classification. Further conjunction analyses revealed enhanced activity in a sub-area of the left IFG_{tri} specifically for the accurate classification of chimpanzee calls compared to human voices. Our data therefore reveal distinct frontal mechanisms that shed light on how the human brain evolved to process non-verbal language.

Author contributions

CD and LC were involved in every steps of the study including experimental design, programming, data acquisition, data analysis and redaction of the first draft of the manuscript and subsequent editing. EP helped design the model-based MRI analyses and interpret the results. TG and DG were involved in the experimental design and study planification. All authors wrote and edited the manuscript.

Introduction

Processing and understanding non-verbal language are fundamental aspects of everyday life in human (1) and animal (2, 3) communication. Their importance can sometimes even be greater than that of verbal communication since a short, powerful in-context vocal burst, for instance, an urgency signal, can easily be noticed and understood by other individuals (2). A critical part of non-verbal language can therefore be represented by 'affective' communication, especially through affective vocalizations, which are of particular interest for cross-species research. Indeed, the ability to express and understand such vocalizations is shared by several primate species, particularly Hominids, a taxonomic family that includes humans and other great apes (4, 5). Such commonalities therefore open a critical window into the investigation of human brain structures recruited by non-verbal communication, for instance by studying these crucial abilities to perceive, process and subsequently categorize and classify affective vocalizations expressed by primate species. These abilities are known to recruit superior temporal, orbitofrontal and inferior frontal cortices in humans (6-9) while these brain areas evolved a lot in primates (10, 11). We will now detail the particular importance of studying cross-species non-verbal language processing and categorization taking place in the frontal cortex of humans.

The *Hominidae* clade appeared between 13 and 18 million years ago (12). Encompassing all living great apes including humans (*Homo sapiens*), chimpanzees (*Pan troglodytes*), bonobos (*Pan Paniscus*), gorillas (*Gorilla subs*), and orangutans (*Pongo subs*), as well as our extinct ancestors, this unique primate taxon is key to understanding the evolution of human behaviour, physiology, communication and cognitive abilities. Very few studies have used bonobo vocalizations as stimuli (13), despite sharing the same phylogenetic proximity to *Homo sapiens* with chimpanzees, their behaviour repertoire—of which gestures can be decoded by humans (14)—including their vocal communication are noticeably different (15-18). Despite a larger and more folded brain compared to other great ape species, human neuroanatomical traits are mainly considered to belong to a continuum in the primate brain evolution (11, 19). For instance, findings in anatomical magnetic resonance imaging (MRI) have demonstrated the existence of a large frontal cortex in all great ape species—humans included(11)—emphasizing the particular interest of a comparative approach to investigate anatomical structures and related functions

of the frontal regions. Moreover, the functions of the frontal lobe, often associated to problem solving, emotion processing and especially evaluative judgment, communication and language or even motor and sexual behaviours (6, 20-25), as well as their related brain structures are shared by most primate species. This includes two critical brain structures that are the focus of this article: the orbitofrontal cortex (OFC) and the inferior frontal gyrus (IFG).

Existing in phylogenetically distant non-human primate species such as rhesus macaques (*Macaca mulatta*) (26), the OFC has similar neuroanatomical architecture and functions across the primate family tree. From humans to monkeys, studies have highlighted the roles of OFC in emotional memory (20, 21), emotional expression (9, 27), executive functions (20) and integration of contextual information in emotional evaluation (8). Interestingly, despite these shared evolutionary OFC functions in primate species, its role in heterospecific affective recognition, such as affective vocalizations, has rarely been investigated. In fact, recent functional MRI data have pointed out a greater enhancement of activity in OFC, in particular of its medial part, in the human identification of emotional voices compared to affective animal vocalizations including positive and negative calls expressed by chimpanzees, macaques and cats (*Felis catus*) (28, 29). More investigations on the role of the human OFC in this context are thus crucially needed.

Functionally and anatomically connected to the OFC (30), the IFG is also present in great apes as well as in monkey species (31). Yet, unlike the OFC, the left IFG is most prominently linked to speech production (Broca's area) in humans (32), the only species 'capable' of a complex and sophisticated language. Hence, in addition to likely shared functions such as decision formation (6, 33), inhibition (34, 35) and emotional judgement (8, 36-38) shaped by natural selection, the IFG also became specialized in semantic auditory processing in the human lineage in the course of evolution (7, 39, 40). Because the current roles of human IFG are linked to both the *Hominidae* and the specific *Homo sapiens* evolutionary histories (41), this frontal region, together with the OFC, is of high interest to investigate conspecific and heterospecific identification mechanisms. Noteworthy is the fact that these specific frontal regions have strong anatomical ties with temporal lobe regions that are crucial in processing vocalizations, especially when they are biologically relevant (23, 30, 36, 42). Besides the importance of

92 OFC and IFG regions in the evolution of primate brains, comparative and integrative approaches to
93 investigate the current functions of these specific frontal regions are still missing. This is especially true
94 for auditory affective processing (43), species categorization and by extension non-verbal
95 communication comprehension in humans—excluding sign language.
96 The present study focused on the processing and subsequent categorization of primate vocalizations in
97 human OFC and IFG using fMRI. To do so, we asked participants to categorize four primate species
98 (human, chimpanzee, bonobo, and macaque) through their affective vocalizations. Non-verbal sounds—
99 namely affective vocal bursts—were selected as human vocalizations to match as well as possible the
100 nature of our primates' vocalizations stimuli. Research on vocal production and perception has indeed
101 demonstrated that non-verbal vocalizations expressed by humans are similar to those expressed by other
102 mammalian species, non-human primates included, especially in affiliative (e.g., play) or agonistic
103 contexts (e.g., aggression) (44). Interestingly, as most animal vocalizations are expressed in a
104 motivational or affective context, existing literature has remained focused on the human recognition of
105 affects in heterospecific vocalizations while neglecting humans' ability to identify other species
106 independently of affect (13, 29, 45-49). Hence, in light of previous literature as well as taking into
107 account the commonalities and differences of the selected four primate species in their evolutionary
108 path, we predicted: i) a behavioural gradient reflecting phylogenetic distance from humans for the
109 species with a higher probability of correctly categorizing human, then chimpanzee, bonobo and finally
110 macaque affective vocalizations (13, 46, 48); for similar reasons, we predicted that chimpanzee and
111 bonobo vocalizations should be more confused with each other than with macaque calls; ii) neural
112 correlates of the probability of correctly categorizing the four primate species in the OFC and IFG,
113 especially in the medial OFC (28, 29) and $IFG_{tri/op(50)}$, respectively; iii) a gradient of activity in the *pars*
114 *triangularis* and *opercularis* of the IFG when comparing the processing and correct categorization of
115 each non-human primate species' vocalizations to human voices using conjunction analyses, both
116 subparts being crucially involved in this process (37, 50).

Results

The present study aimed at assessing the ability of humans to accurately classify human and more importantly other primate calls, in the present case chimpanzee, bonobo, and macaque vocalizations (Fig.1**a**) and how frontal brains areas may underlie such successful non-verbal stimuli categorization. Behavioural analyses were performed using a Species factor (human, chimpanzee, bonobo, macaque) interacting with the Affective context factor for each vocalization (affiliative, agonistic 'threat', agonistic 'distress') in a generalized linear mixed-effects modelling of the accuracy data ('1', correct response; '0', incorrect response) and a linear mixed-effects modelling of the confusion data. This statistical procedure was used to better assess the probability of correctly categorizing each species' vocalizations as well as the pattern of confusion between each species, respectively. Following similar reasoning, we used the trial-level probability of correct species categorization in model-based fMRI methodology. We tested the specific frontal mechanism underlying the combined processing and accurate classification of each non-human primate species vocalizations compared to human voices using conjunction analyses. Both analyses were conducted in our regions of interest (ROI), namely in the bilateral IFG (*pars opercularis*, *triangularis*, *orbitalis*) and OFC (superior, middle, medial) using masked second-level analyses with voxelwise corrected statistics ($p<.05$ False Discovery Rate correction 'FDR', k>5 voxels). Selected low-level acoustics (mean and standard deviation of stimulus energy and fundamental frequency) were used as covariates of no interest for behavioural and neuroimaging analyses to better control our data for low-level vocal fluctuations. Statistical modelling power is reported for fixed effects ('R^2c') and for both fixed and random effects taken together ('R^2m').

Behavioural results

Accuracy data

As predicted, the generalized linear mixed-effects on accuracy revealed a significant effect of Species factor ($\chi^2(3)=222.78$, $p<.0001$, $R^2c=56.38\%$ and $R^2m=61.10\%$). All complementary results of this model

143 can be found in Supplementary Table 1. We then tested the contrasts of interest according to our
144 behavioural hypothesis namely the impact of phylogenetic proximity on accurate species categorization:
145 our results highlighted a higher probability of correctly categorizing human compared to the
146 vocalizations of each non-human primate ($\chi^2(1)=128.96$, $p_{Bonf}<.0001$; human > chimpanzee:
147 $\chi^2(1)=95.89$, $p_{Bonf}<.0001$; human > bonobo: $\chi^2(1)=199.51$, $p_{Bonf}<.0001$; human > macaque: $\chi^2(1)=79.40$,
148 $p_{Bonf}<.0001$). We additionally compared each non-human primate species with each other and found a
149 higher probability of correct categorization for chimpanzee compared to bonobo ($\chi^2(1)=52.64$, p_{Bonf}
150 $<.0001$), and macaque compared to bonobo vocalizations ($\chi^2(1)=18.99$, $p_{Bonf}<.0001$). No difference was
151 observed when comparing the probability of correct species categorization between chimpanzee and
152 macaque vocalizations ($\chi^2(1)=1.84$, $p_{Bonf}=.17$, Fig. 1b).

153 Confusion data analyses were computed by considering species miscategorization, namely one species'
154 vocalization being categorized as belonging to another species (Fig.1**c**). The confusion for human voices
155 was not significant ($\chi^2(3)=1.65$, $p=.65$), meaning that these were not significantly miscategorised with
156 any other species. Confusion concerning chimpanzee vocalizations showed a significant main effect of
157 Species ($\chi^2(3)=265.79$, $p<.0001$; $R^2c=16.41\%$ and $R^2m=24.64\%$), showing that these were mostly
158 miscategorised as bonobo vocalizations ($\chi^2(1)=149.52$, $p_{Bonf}<.0001$), and then as macaque ($\chi^2(1)=47.11$,
159 $p_{Bonf}<.0001$) vocalizations (for chimpanzee confusions, bonobo > macaque: $\chi^2(1)=15.34$, $p_{Bonf}<.0001$),
160 but not as human voices ($\chi^2(1)=0.21$, $p_{Bonf}>.99$). Confusion for bonobo vocalizations showed a
161 significant main effect of the Species factor ($\chi^2(3)=107.96$, $p<.0001$; $R^2c=24.50\%$ and $R^2m=28.95\%$)
162 and specific confusion was the highest with macaque ($\chi^2(1)=114.70$, $p_{Bonf}<.0001$) and then chimpanzee
163 ($\chi^2(1)=111.28$, $p_{Bonf}<.0001$) vocalizations (for bonobo confusions, macaque > chimpanzee: $\chi^2(1)=5.33$,
164 $p_{Bonf}<.05$) but no significant confusion with human voices was observed ($\chi^2(1)=0.06$, $p_{Bonf}>.99$).
165 Confusion for macaque vocalizations showed a main effect of the Species factor ($\chi^2(3)=469.68$, $p<.0001$;
166 $R^2c=29.01\ \%$ and $R^2m=30.65\%$) with highest confusion with bonobo ($\chi^2(1)=565.04$, $p_{Bonf}<.0001$)
167 followed by chimpanzee ($\chi^2(1)=145.96$, $p_{Bonf}<.0001$) vocalizations (for macaque confusions, bonobo >

chimpanzee: $\chi^2(1)=87.34$, $p_{Bonf}<.0001$). No confusion with the human voice reached significance ($\chi^2(1)=0.04$, $p_{Bonf}>.99$). All other specific confusion effects can be found in Supplementary Table 2.

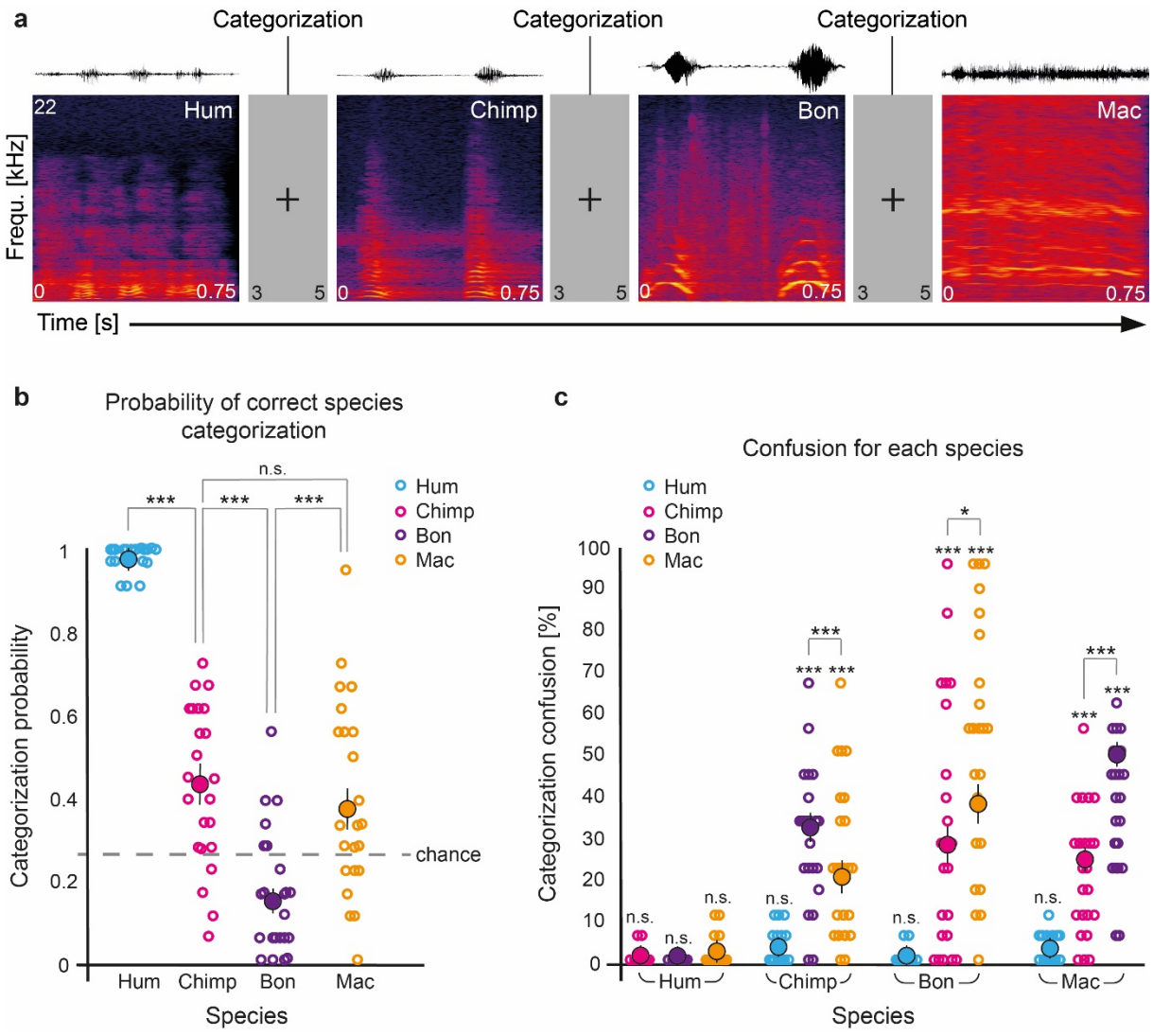

Figure 1. Experimental procedure and behavioural results of the probability of correct species categorization and confusions. a, Example of four consecutive experimental task trials (inter-trial interval of 3-5s) for which the participants had to categorize the species' stimulus (750ms duration) for each trial (pseudo-randomized species order) and spectrogram example for each species. **b,** Probability of the correct categorization of each species (*y* axis) modelled across all participants, trials and species (i.e., human, chimpanzee, bonobo, macaque); Each circle represents a participant's averaged value per species, full circles represent the general average per species across participants ± the standard error of the mean, chance level is 25% (grey dotted line). **c,** Percentage of categorization confusion (*y* axis) specific to each species (*x* axis); Each circle represents a participant's averaged value, full circles

181 represent the general average per species across participants ± the standard error of the mean. Hum:
182 human; Chimp: chimpanzee; Bon: bonobo; Mac: macaque. ***p<.001, *p<.05, n.s.: non-significant.

183

184 ***Neuroimaging results using IFG and OFC as regions of interest***

185 We first used a model-based approach in order to characterize the general frontal mechanism underlying
186 the accurate categorization of primate vocalizations by human participants (see model 1 in the methods
187 section). To do so, we modelled all trials with the sample-specific fitted probability of a correct vs.
188 incorrect species categorization as a covariate of interest for each trial's onset. This covariate was then
189 taken as the main regressor of interest to masked group-level analyses to reveal frontal patterns of
190 activity related to the general human neural mechanism of classifying human, chimpanzee, bonobo, and
191 macaque vocalizations. These fitted probability values were obtained across participants and species by
192 predicting accuracy data at the trial level, therefore including all trials, correct and incorrect, in a logistic
193 regression analysis. Fixed effects included the Species and Affective context factors and covariates of
194 no interest (mean and standard deviation of vocalization energy and fundamental frequency) with
195 random effects characterizing the identity of each participant (random intercept) and each stimulus
196 (random slope).

197 Activity correlating with the probability of correctly categorizing each species' vocalizations was
198 revealed in the right IFG_{tri} (Fig.2**b**) and bilateral IFG_{orb} (Fig.2**abd**) as well as in the bilateral OFC_{med}
199 (Fig.2**c**). Anti-correlated activity was revealed in a large left IFG_{tri}, IFG_{op} cluster (Fig.2**ef**) and to a lesser
200 extent in the left IFG_{orb} (Fig.2**e**), right IFG_{op} and IFG_{orb} (Fig.2**fh**) and in the right OFC_{mid} (Fig.2**b**) and
201 left OFC_{sup} (Fig.2**e**). See Supplementary Table 3 for cluster coordinates.

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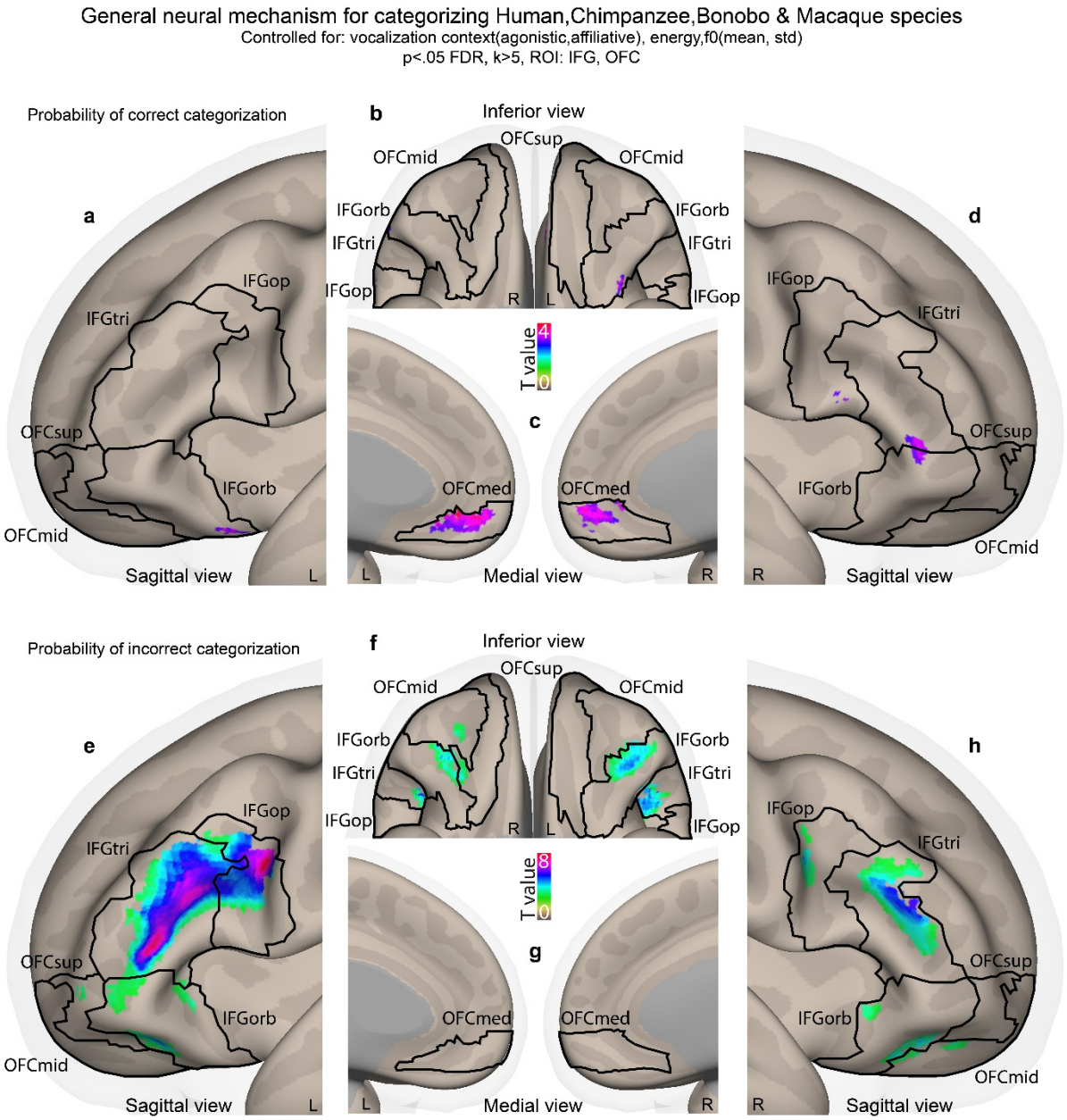

Figure 2. Model-based neural correlates and anti-correlates of the probability of correctly categorizing each species' vocalizations in the IFG and OFC. abcd, Trial-by-trial correlates of the probability of correct species categorization. **efgh,** Trial-by-trial anti-correlates of the probability of correct species categorization. Data of this analysis were computed by using a modelling of species categorization accuracy across all participants, species (Species factor) and trials including the Affective context factor and trial-level covariates of no interest (mean and standard deviation of the vocalization energy and fundamental frequency). Subsequently, the fitted probability values of this model were used as a parametric modulator of interest for each trial's onset, further taken as main regressor in second-

212 level analyses. Colorbars illustrate t-value statistics. All activations thresholded at a voxelwise $p<.05$
213 FDR, k>5 voxels, masked by IFG and OFC regions of interest (k=9635 voxels in total). IFG: inferior
214 frontal gyrus; tri: pars triangularis; op: pars opercularis; orb: pars orbitalis; OFC: orbitofrontal cortex;
215 med: medial; mid: middle; sup: superior.

216

217 We then computed two conjunction analyses with each non-human primate species compared to human
218 voice categorization. In these analyses, enhanced activations for each non-human primate species was
219 tested while driving the conjunction but only the [(chimpanzee > human) > (bonobo > human) >
220 (macaque > human) vocalizations] contrast showed significant results (see model 2 in the methods
221 section). This conjunction revealed left-lateralized IFG_{tri} and IFG_{op} as well as right IFG_{tri} activity for the
222 processing of the vocalizations (i.e., general processing displayed as white-to-pink activations,
223 Fig.3**abd**) while enhanced activity for correctly categorized species (see model 3 in the methods section)
224 was only found in left IFG_{tri} (i.e., correct categorization displayed as black-to-white activations, Fig.3**a**).
225 No enhanced signal was observed in the OFC. Other combinations of non-human primate vs. human
226 species conjunction contrasts did not yield to any above-threshold voxels. Mean and standard deviation
227 of each vocalization's energy and fundamental frequency were used as trial-level covariates of no
228 interest in these statistical analyses as well. See Supplementary Table 4 for cluster coordinates.

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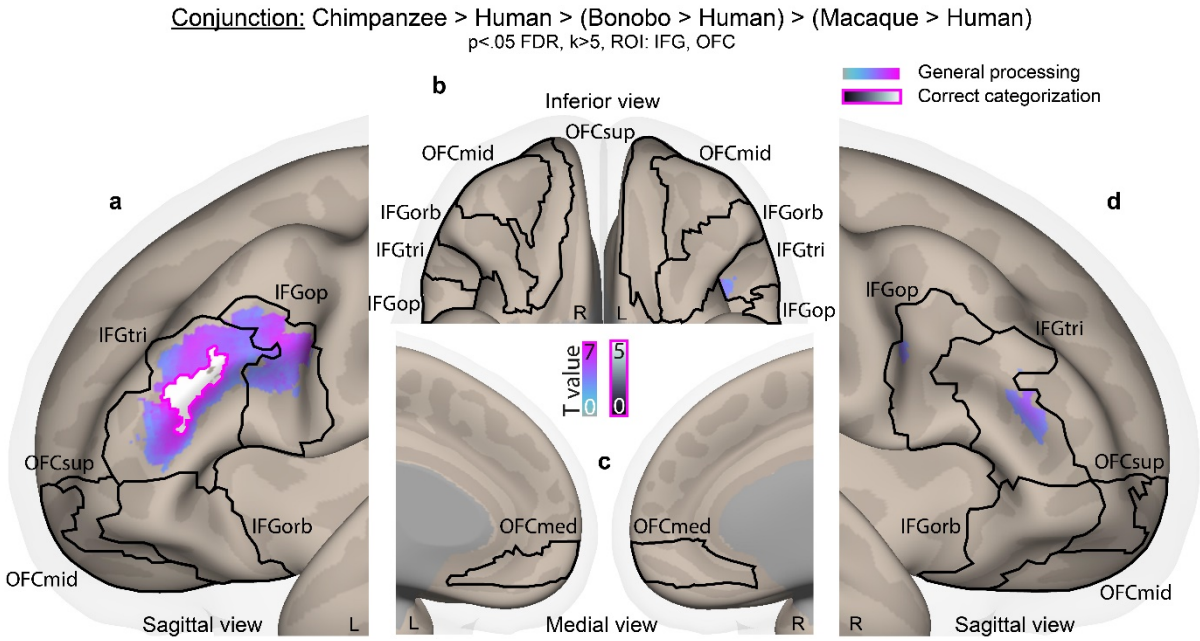

Figure 3. Conjunction results of the processing and correct categorization of non-human primates compared to human vocalizations in the IFG and OFC. abcd, Conjunction analysis for the processing (white-to-pink activations, all trials of each species) and correct species categorization (black-to-white activations with pink outline, correct trials only) of the contrasts [(chimpanzee > human) > (bonobo > human) > (macaque > human) vocalizations]. No above-threshold voxels were found for [bonobo > human] or [macaque > human] contrasts driving the conjunction analyses. For both models (species processing; correct species categorization), trial-level covariates of no interest included the mean and standard deviation of the vocalization energy and fundamental frequency. Colorbars illustrate t-value statistics. All activations thresholded at a voxelwise *p*<.05 FDR, k>5 voxels, masked by IFG and OFC regions of interest (k=9635 voxels in total). IFG: inferior frontal gyrus; tri: pars triangularis; op: pars opercularis; orb: pars orbitalis; OFC: orbitofrontal cortex; med: medial; mid: middle; sup: superior.

The comparisons between the processing (all trials) or the correct categorization (correct trials only) of the vocalizations of each non-human species compared to those of humans, and of human voices compared to the vocalizations of each non-human primate species are reported in Fig.S1 and Fig.S2, respectively. Activations specific to the processing and correct categorization of each non-human primate species or between each non-human primate species are reported in Fig.S3 and Fig.S4, respectively.

Discussion

The present study was designed to clarify the importance of primate vocalizations processing and classification by humans as a proxy for the more general treatment of human non-verbal communication. In fact, the processing of primate vocalizations by humans might boost our understanding of non-verbal communication in today's *Homo sapiens* and inform our reconstruction of our last common ancestor with other Hominids. To operationalize such a research objective, we investigated the behavioural and frontal brain mechanisms in modern humans underlying the vocal recognition of non-human primates' vocalizations, considering their phylogenetic proximity to the human species. Our data highlighted the evolutionary shared history of our species with the communication system of other primates, particularly other great apes, with both the recognition and classification processes of hominid vocalizations involving the medial orbitofrontal and bilateral inferior frontal cortex, especially the *pars triangularis*. Behavioural data emphasized the astonishing ability of human participants to categorize chimpanzee and macaque calls above chance level while it was not the case for bonobo vocalizations. Despite the close phylogenetic proximity of this species with *Homo sapiens*, the peculiar acoustical structure of bonobo calls may have prevented modern humans from recognizing them, yielding to miscategorization. Indeed, confusion matrices showed that, despite their close phylogenetic relationship to chimpanzees, bonobo vocalizations were in fact often confused for those of macaques. This peculiarity in the processing of bonobo vocalizations has also been reported in previous literature showing that human adults are highly sensitive to pitch information for discriminating the arousal of primate babies' cries (13). In fact, human participants rated bonobo infant calls as more distressful in comparison to those of humans or chimpanzees and after further acoustical analyses, the authors found that bonobo infants' calls had higher pitched vocalizations compared to those of human and chimpanzee babies, both species sharing more similar acoustical features (13). Such acoustical divergence of bonobos among non-human primates and especially the increased fundamental frequency of their calls may well have its origin in the shorter length of the larynx of this species (15). Interestingly in our study, chimpanzee calls were not better categorized by human participants than those of a more evolutionary distant species such as

rhesus macaques. This was especially surprising considering that previous studies have mostly found a better recognition rate for chimpanzee vocalizations compared to the calls of other non-human primates (46, 51). Hence, our behavioral analysis suggests that the capacity of modern humans to accurately identify non-human primate calls could rely more heavily on acoustic similarity rather than phylogenetic proximity alone (52).

To assess the frontal brain mechanisms involved in the general processing of human voice and non-human primate vocalization recognition, we turned to computational modelling and more precisely to model-based fMRI analyses. These data pointed to a frontal network including the bilateral medial OFC for the correct recognition and categorization of human voices and non-human primate vocalizations. This first result suggests that the medial OFC has a central role in the accurate categorization of primate calls, extending previous fMRI results that showed an enhancement of activity in OFC regions—especially of the medial part—for the discrimination of emotions in human, chimpanzee, macaque, and cat vocalizations (28, 29). Other frontal brain areas underlying the probability of accurate species categorization included small clusters of the bilateral IFG_{orb} as well as the right IFG_{op} and IFG_{tri}. Frontal brain areas underlying miscategorization and/or what could be labelled as 'hesitation' were found in large portions of the bilateral IFG, especially in the IFG_{tri} which is coherent with existing literature (53). This result is also supported by our conjunction analyses, which allowed a more concise and focused multi-contrast approach to pinpoint the specific frontal brain mechanisms that may underlie the processing as well as accurate recognition and categorization of non-human primate vocalizations compared to the human voice. These analyses revealed large, similar bilateral IFG_{tri} clusters of activity when creating a hierarchy for processing chimpanzee, bonobo and macaque vocalizations each compared to the human voice—namely, contrasting (chimpanzee > human) > (bonobo > human) > (macaque > human) at the same time. Interestingly, this conjunction contrast also revealed a difference in the hierarchy between the accurate recognition of chimpanzee vocalizations and those of bonobos and macaques when each was compared to the human voice in a subpart of the left IFG_{tri}. In the literature, the IFG_{tri} was repeatedly involved when human participants have to make a decision based on vocal signals, for instance when human participants discriminate or categorize human vocal emotion (37, 50)

304 or when they implicitly or explicitly process human emotional voices (7). Causal links between IFG_{tri}
305 functioning and emotion recognition were also revealed in the literature (54). Noteworthy is the fact that
306 activity in the left IFG_{tri} also translates a level of uncertainty when decisional processes occur (53, 55-
307 57). Combining our behavioural and neuroimaging results, it seems extremely plausible that decisional
308 uncertainty was peaking when human participants were categorizing non-human primate vocalizations.
309 We therefore think that according to our results and to the existing literature, activity in the IFG_{tri} might
310 underlie both categorization uncertainty as revealed by anti-correlates of the probability of accurate
311 species recognition in the model-based neuroimaging results, as well as decisional processes that lead
312 to an accurate species recognition in a very concise region of the left IFG_{tri}, as highlighted by our
313 conjunction results. Therefore, OFC and IFG brain areas—especially IFGtri activity—may be the
314 necessary biological and functional 'hardware' allowing *Homo sapiens* to classify and integrate non-
315 verbal communication, be it human voice or other primate vocalizations. Such ability may then have
316 been co-opted for the treatment of the proto-language used by our human ancestors, although precisely
317 how close this proto-language was from to today's non-human primates vocalizations remains an open
318 question , with a question mark regarding a potential interaction with between-species acoustical
319 differences (52). We contend that the common activity we evidenced in the OFC and IFG across stimuli
320 suggests that such proto-language may have shared acoustic properties with non-human primate
321 vocalizations.
322 Even though our results shed new light on the origins of human non-verbal communication, our study
323 suffered from several limitations. Such limitations include the absence of higher temporal resolution,
324 the absence of other great apes as stimuli (for instance gorillas and/or orangutans) and the absence of
325 highly specific acoustic distance assessment. Also, the time-course of such frontal mechanisms
326 underlying non-verbal communication in humans should be investigated.
327 To conclude, the present study revealed the existence of distinct mechanisms at play in the human frontal
328 cortex for the integration and further categorization of non-human primate vocalizations. In fact,
329 computational modelling of the fMRI data allowed a clear distinction between accurate categorization
330 on the one hand and miscategorization processes on the other hand, as revealed by bilateral medial OFC
331 and left IFG_{tri}, respectively. Combined with our behavioural data, evidence converges toward a

332 preserved ability of *Homo sapiens* to recognize the calls of species close to his ancestors that were most
333 likely very similar to those of today's non-human primate vocalizations. Natural selection might also
334 have led to specific anatomical adaptations in some non-human primates across time, and the shorter
335 larynx of bonobos leading to the significantly increased fundamental frequency of their calls is a well-
336 fitting example, especially in the context of the present study. Therefore, a combination of phylogenetic
337 and acoustical proximity may be necessary for humans to recognize and successfully categorize the calls
338 of non-human primates, including those of great apes. Overall, the present study substantially
339 contributes to the understanding of primate calls' recognition by modern humans as a proxy for more
340 general non-verbal communication mechanisms in *Homo sapiens*.

341

342 **Material and Methods**

343 ***Experimental procedure and paradigm***

344 Participants laid comfortably in a 3T scanner and heard a total of seventy–two stimuli in pseudo-
345 randomized order through MRI-compatible earphones (Sensimetrics Corporation, Gloucester, MA,
346 USA) at a sound pressure level of 70dB. Participants were instructed to identify the species that
347 expressed the vocalizations using a response box (Current Designs, Inc., Philadelphia, PA, USA). For
348 instance, the instructions could be "Human – press 1, Chimpanzee – press 2, Bonobo – press 3 or
349 Macaque – press 4". There were four different mappings of the keys that were randomly assigned across
350 participants. In a 3 – 5 second interval (jittering of 400 ms) after each stimulus, participants were asked
351 to categorize the species. If the participant did not respond during this interval—namely a missed trial,
352 the next stimulus followed automatically and the value of the response was '0' while '1' coded a correct
353 response, '2' an incorrect response (Fig.1**a**).

354 ***Stimuli***

355 Seventy-two vocalizations of four primate species (human, chimpanzee, bonobo and rhesus macaque)
356 were used in this study. The eighteen human voices were expressed by two male and two female actors,
357 obtained from a non-verbal (affective vocal burst) validated set of Belin and collaborators (58). Non-

358 linguistic vocalizations were selected as human voice stimuli due to their acoustic and perceptual
359 proximity with the other mammalian calls, non-human primates included (44). The eighteen selected
360 chimpanzee, bonobo and rhesus macaque vocalizations contained single calls or two call sequences
361 produced by 6 to 8 different individuals in their natural environment. For each non-human primate
362 species, the stimuli were either produced in an affiliative context or produced in an agonistic context
363 (threating or distressful). All vocal stimuli were standardized to 750 milliseconds using PRAAT
364 (www.praat.org) but were not normalized in order to preserve the 'naturality' of the sounds (59).

365 ***Participants***

366 Twenty-five right-handed, healthy, either native or highly proficient French-speaking participants took
367 part in the study. One participant was excluded because he had no correct response at all and may have
368 fallen asleep, while another participant was excluded due to incomplete scanning and technical issues,
369 leaving us with twenty-three participants (10 female, 13 male, mean age 24.65 years, SD 3.66). All
370 participants were naive to the experimental design and study, had normal or corrected-to-normal vision,
371 normal hearing and no history of psychiatric or neurologic incidents. Participants gave written informed
372 consent for their participation in accordance with ethical and data security guidelines of the University
373 of Geneva. The study was approved by the Ethics Cantonal Commission for Research of the Canton of
374 Geneva, Switzerland (CCER) and was conducted according to the Declaration of Helsinki.

375

376 ***Statistical analysis***

377 Behavioural data were analysed using R studio software (60). In order to test our hypotheses regarding
378 the impact of phylogenetic distance on species categorization, we performed mixed-effects models
379 analyses of the 'lme4' package (61) on accuracy and confusion (one accuracy column: '1', correct
380 response; '0', incorrect response; four confusion columns: '1', confusion with the species, '0' no
381 confusion with the species, for each of the four species column) and reaction times data (for correct,
382 incorrect trials and specific confusion for each species) with Species (human, chimpanzee, bonobo,
383 macaque) and Affective context (affiliative and agonistic) as interacting fixed factors, four covariates

(mean energy of each species, mean fundamental frequency of each species, energy standard deviation of each species, fundamental frequency standard deviation of each species) and the participants' and the stimuli identity as random factors (random intercept and random slope, respectively). The inclusion of the sex and age of the participants for which we had no specific hypothesis in data modelling did not yield to a significantly better model neither for accuracy ($\chi^2(2)=.81$, $p=.66$) nor for reaction times data ($\chi^2(2)=.01$, $p=1$) and these random effects were therefore discarded from the analyses. The same model was used to analyse accuracy, confusion and reaction times data, except that a logistic regression (generalized linear mixed-effects models, 'glmer') was used for accuracy and a linear regression (linear mixed-effects models, 'lmer') for specific pairs of species confusion (four models in total) and for reaction times. Then, we used specific contrasts computed using the 'phia' package (62) to compare between-species categorization, testing our hypothesis of an impact of phylogenetic proximity on species categorization. Contrasts therefore included human vs. non-human primate planned comparisons: [human > chimpanzee, bonobo, macaque vocalizations], [human > chimpanzee vocalizations], [human > bonobo vocalizations], [human > macaque vocalizations]; non-human primate vs. human comparisons: [chimpanzee > human vocalizations], [bonobo > human vocalizations], [macaque > human vocalizations]. These inverse contrasts actually yield to a sign-reversal of the difference estimate of the original contrast for accuracy data. For confusion data, contrasts were computed to uncover any difference between one human or non-human primate species compared to the remaining species: [Confusion for human vocalizations: chimpanzee response ≠ bonobo response ≠ macaque response], [Confusion for chimpanzee vocalizations: human response ≠ bonobo response ≠ macaque response], [Confusion for bonobo vocalizations: human response ≠ chimpanzee response ≠ macaque response], [Confusion for macaque vocalizations: human response ≠ chimpanzee response ≠ bonobo response]. All contrasts were corrected for multiple comparisons using a Bonferroni adjustment method implemented in the 'phia' package (adjustment="Bonf") and *p*-value is accordingly reported as 'p_{Bonf}'. Reaction times data were analysed using the same contrasts and are reported in Supplementary Material.

410 ***Image acquisition***

411 Structural and functional brain imaging data were acquired by using a 3T scanner Siemens Trio,
412 Erlangen, Germany with a 32-channel coil. A 3D GR\IR magnetization-prepared rapid acquisition
413 gradient echo sequence was used to acquire high-resolution (0.35 x 0.35 x 0.7 mm^3) T1-weighted
414 structural images (TR = 2400 ms, TE = 2.29 ms). Functional images were acquired by using fast fMRI,
415 with a multislice echo planar imaging sequence 79 transversal slices in descending order, slice thickness
416 3 mm, TR = 650 ms, TE = 30 ms, field of view = 205 x 205 mm2, 64 x 64 matrix, flip angle = 50
417 degrees, bandwidth 1562 Hz/Px.

418 ***Wholebrain image analysis***

419 Functional images were analysed with Statistical Parametric Mapping software (SPM12, Wellcome
420 Trust Centre for Neuroimaging, London, UK). Preprocessing steps included realignment to the first
421 volume of the time series, slice timing, normalization into the Montreal Neurological Institute (MNI)
422 space (63) using the DARTEL toolbox (64) and spatial smoothing with an isotropic Gaussian filter of 8
423 mm full width at half maximum. To remove low-frequency components, we used a high-pass filter with
424 a cut-off frequency of 128s. Three general linear models were used to compute first-level statistics.

425 *Model 1: model-based categorization probability of each species, including all trials*

426 In this model, the probability of correctly categorizing each species in each production context was
427 modelled using the 'fitted' function of the 'stats' package (65) to obtain the fitted probability values
428 from the behavioural accuracy data described in the behavioural data analysis section. This modelling
429 was performed by using each trial (N=72) of each fMRI session (N=1) of each participant (N=23) with
430 a binary '1' and '0' coding for the correct and incorrect species categorization, respectively, as
431 dependent variable. As mentioned above, the model included fixed effects, namely the interaction
432 between the Species factor (human, chimpanzee, bonobo, macaque) and the Affective context factor
433 (affiliative, agonistic) and four covariates of interest (in this order: mean energy of each species, mean
434 fundamental frequency of each species, energy standard deviation of each species, fundamental
435 frequency standard deviation of each species). Random effects included the participants' and the stimuli

436 identity (random intercept and random slope, respectively). The sample-specific matrix (participants per
437 trials=23*72=1656 lines) was then cut to the corresponding participant-specific matrix (72 lines). Model
438 1 therefore included two 72-lines regressors, namely the onsets of each trial in its order of appearance—
439 modelled by using a boxcar function and convolved with the hemodynamic response function time-
440 locked to the onset of each stimulus—and the corresponding modelled probability of correctly
441 categorizing each species as a covariate of interest. Six motion parameters were included as regressors
442 of no interest to account for movement in the data and our design matrix therefore included a total of 8
443 columns plus the constant term. The regressor of interest (modelled probability of correctly categorizing
444 each species) was used to compute a simple contrast for each participant, leading to separate main effect
445 of the probability of correctly categorizing each species. This simple contrast was then taken to a one-
446 sample t-test second-level analysis in which variance was set to 'unequal'.

447 *Model 2: processing of all species, including all trials*

448 In this model, each event was modelled by using a boxcar function and was convolved with the
449 hemodynamic response function, time-locked to the onset of each stimulus. Separate regressors were
450 created for all trials of each species (Species factor: human, chimpanzee, bonobo, macaque) and
451 production context (Affective context factor: affiliative, agonistic) and four covariates each (mean
452 energy of each species, mean fundamental frequency of each species, energy standard deviation of each
453 species, fundamental frequency standard deviation of each species) for a total of 47 regressors. The
454 means and standard deviations of the fundamental frequency and the energy of the vocalizations were
455 extracted using the extended Geneva Acoustic parameters set, which is defined as the optimal acoustic
456 indicators related to human voice analysis (GeMAPS (66)). This set of acoustical parameters was
457 selected based on i) their potential to index affective physiological changes in voice production, ii) their
458 proven value in former studies as well as their automatic extractability, and iii) their theoretical
459 significance.
460 Six motion parameters were included as regressors of no interest to account for movement in the data
461 and our design matrix therefore included a total of 66 columns plus the constant term. The species
462 regressors were used to compute simple contrasts for each participant, leading to separate main effects

463 of human, chimpanzee, bonobo and macaque vocalizations for each production context (12 simple
464 contrasts). Covariates were set to zero in order to model them as no-interest regressors. These simple
465 contrasts were then taken to a flexible factorial second-level analysis in which there were three factors:
466 the Participants factor (data independence set to 'yes', variance set to 'unequal'), the Species factor and
467 the Affective context factor (for both factors: data independence set to 'no', variance set to 'unequal').
468 For this first model, the main effect of the Species factor was computed in the flexible factorial
469 modelling while the Affective context factor was modelled but excluded from the results because we
470 did not have any hypothesis regarding this factor and because each context modality contained only 6
471 trials per species.

472 *Model 3: correct categorization of each species, including only correct trials*

473 Separate regressors were created for each correctly categorized species (Correct Species factor: human
474 hits, chimpanzee hits, bonobo hits, macaque hits vocalizations) for each production context (Affective
475 context factor: affiliative, agonistic) and four covariates each (mean energy of each species, mean
476 fundamental frequency of each species, energy standard deviation of each species, fundamental
477 frequency standard deviation of each species) as well as a regressor containing a concatenation of
478 categorization errors across species for a total of 44 regressors. Regressors were modelled by using a
479 boxcar function and convolved with the hemodynamic response function, time-locked to the onset of
480 each stimulus. Six motion parameters were included as regressors of no interest to account for movement
481 in the data and our design matrix therefore included a total of 51 columns plus the constant term. The
482 regressors of interest (Correct Species factor) were used to compute 8 simple contrasts for each
483 participant, leading to separate main effects of human hits, chimpanzee hits, bonobo hits and macaque
484 hits vocalizations for each production context. Covariates were set to zero in order to model them as no-
485 interest regressors. These simple contrasts were then taken to a flexible factorial second-level analysis
486 in which there were three factors: the Participants factor (independence set to 'yes', variance set to
487 'unequal'), the Correct Species factor and the Affective context factor (for both factors: independence
488 set to 'no', variance set to 'unequal'). For this third model, the main effect of the Correct Species factor
489 was computed in the flexible factorial modelling while the Affective context factor was modelled but

excluded from the results because we did not have any hypothesis regarding this factor and because each modality contained only 6 trials per species.

For all three models and to be consistent in our analyses, neuroimaging activations were masked by a binary image including all subparts of the IFG (*pars opercularis*, *triangularis* and *orbitalis*) and OFC (superior, middle and medial) for a total of twelve subregions, 9635 voxels and thresholded in SPM12 by using a voxel-wise false discovery rate (FDR) correction at $p<.05$ and an arbitrary cluster extent of $k>5$ voxels to remove extremely small clusters of activity. Region masks were extracted using the 'automated anatomical labelling' ('aal') atlas (67) implemented in the 'WFU_Pickatlas' toolbox (https://www.nitrc.org/projects/wfu_pickatlas/). Contrast activations were rendered on semi-inflated brains from the CONN toolbox (68) with black outlines delineating each of our IFG-OFC regions of interest.

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Competing interests

The authors declare no competing interests whatsoever.

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