Vocal convergence in a multi-level primate society: insights into the evolution of vocal

learning

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ABSTRACT

The extent to which nonhuman primate vocalizations are amenable to modification

through experience is relevant for understanding the substrate from which human

speech evolved. We examined the vocal behaviour of Guinea baboons, *Papio papio*,

ranging in the Niokolo Koba National Park in Senegal. Guinea baboons live in a multi-

level society, with units nested within parties nested within gangs. We investigated

whether the acoustic structure of grunts of 27 male baboons of two gangs varied with

party/gang membership and genetic relatedness. Males in this species are philopatric,

resulting in increased male relatedness within gangs and parties. Grunts from

members were more similar within than across social levels (N = 351 dyads for

comparison within and between gangs, and N = 169 dyads within and between

parties), but the effect sizes were small. Yet, acoustic similarity did not correlate with

genetic relatedness, suggesting that higher amounts of social interactions rather than

genetic relatedness promote the observed vocal convergence. We consider this

convergence a result of sensory-motor integration and suggest this to be an implicit

form of vocal learning shared with humans, in contrast to the goal-directed and

intentional explicit form of vocal learning unique to human speech acquisition.

KEY WORDS: *Papio*, primate communication, vocal learning, sensory-motor

integration, speech evolution, implicit learning

INTRODUCTION

One of the key preconditions for the development of speech is the ability to adjust vocal output in response to auditory input. Humans are exceptionally proficient at vocal learning. Although effortless speech learning is confined to the early years [1], humans still possess the ability to imitate sounds voluntarily and acquire further languages throughout their lives. Numerous comparative studies have aimed at elucidating the evolutionary origins of vocal learning within the primate lineage, to uncover the extent to which nonhuman primates reveal evidence for vocal plasticity, and whether such plasticity may be conceived as a pre-adaptation for the evolution of speech [2,3].

Despite considerable research effort, it appears that the ability to learn sounds from auditory experience in most nonhuman primate species is limited. Unlike some humans or some songbird species, nonhuman primates are not obligatory vocal learners that require species-specific auditory input to develop their normal vocal repertoires [4,5]. Early attempts to train a young chimpanzee to produce speech sounds yielded disappointing results and prompted most of the 'ape language' projects to turn to another modality, using either symbol systems or sign languages [6]. Studies of the neural basis of vocal production in different monkey species found that the animals lack the neural connections necessary for the volitional control over the fine structure of vocalizations, although they exert greater control over the usage of calls [reviewed in 2]. One exception to the rule of limited vocal plasticity may be orangutans that have greater control over their vocal apparatus [7,8].

In addition to the limited ontogenetic plasticity, a range of comparative studies within different nonhuman primate species strongly suggests that the motor patterns underlying vocalizations are evolutionarily highly conserved within genera [reviewed in 2]. For instance, the structure of alarm calls of members of the genus *Chlorocebus* differs only marginally between East African vervets, *Chlorocebus pygerythrus* and West African green monkeys, *Chlorocebus sabaeus.* Moreover, in response to a drone naïve West African green monkeys

spontaneously uttered calls that structurally were highly similar to East African vervet "eagle

alarm calls", indicating that the link between the perception of a specific (potentially

dangerous) stimulus and the activation of a given motor program is also conserved [9].

At the same time, subtle modifications in vocal output as a result of auditory

experience appear to be possible. For instance, common marmosets, *Callithrix jacchus,*

increase the amplitude of their calls in noisy environments ["Lombard effect"; ,10,11]. More

importantly, a range of species shows group-specific variations or 'dialects' in their

vocalizations [reviewed in 12], while Japanese macaques matched some of the acoustic

features of calls presented in playbacks [13]. These instances of vocal plasticity have been

described as "vocal accommodation" [12,14,15] or "social shaping" [15], similar to the

observation that humans may involuntarily match the pitch, temporal patterning and prosody

of the people they are talking to.

Following the idea that auditory input may lead to vocal convergence, subjects that

interact more frequently with one another using vocalizations should produce calls that are

more similar to each other than those that interact less frequently. A higher acoustic similarity

may also result from genetic relatedness, however. For instance, highly related subjects may

also have a similar morphology of the vocal production apparatus [16]. Before conclusions

about the role of experience can be drawn, it is necessary to assess whether potential

acoustic variation between individuals can (also) be explained by genetic distance.

To date, only few studies investigated the effects of genetic relatedness and

interaction frequency at the same time. Lemasson and colleagues reported that interaction

frequency but not genetic relatedness accounted for acoustic variation in the calls of

Campbell's monkeys, *Cercopithecus campbelli campbelli* [17]. The reported correlation of

acoustic similarity with grooming frequency may be spurious, however, as data from two

groups (with N = 6 and 4 females, respectively) were pooled, and the correlation was largely

driven by the differences between the groups. Levréro and colleagues [15] studied the

acoustic structure of contact calls in 36 male and female mandrills living in three social

groups. Both genetic relatedness and familiarity impacted acoustic similarity of the species'

'kakak' calls, while retaining cues to kin memberships: playback experiments showed that

subjects responded significantly more strongly to calls recorded from related kin, irrespective

of familiarity [15].

We here set out to assess the impact of social interaction while controlling for genetic

relatedness by comparing the acoustic variation in the grunts of male Guinea baboons, *Papio*

papio. Guinea baboons are an interesting model to examine the influence of auditory

experience and social group membership, as they live in a nested multi-level society with

male philopatry [18]. At the base of the society are 'units' comprising one adult male, 1-6

females, and young. A small number of units, together with bachelor males, form a 'party',

and 2-3 parties make up a 'gang' (Fig. 1a). Assignments to parties and gangs are based on

spatial proximity and affiliative interactions [19]. During affiliative interactions with other group

members, males produce low-frequency tonal grunts (Fig. 1b). Their social structure allowed

us to assess vocal convergence at two social levels, namely within parties and within gangs.

Figure 1. (a) The multilevel social organisation of Guinea baboons. Several units form a

party, and two or more parties form a gang. (b) Spectrogram of grunts from four different

males. Frequency (kHz) on the y-axis, time (s) on the x-axis. The spectrogram was created

using Avisoft-SASLab Pro 5.2 (1.024 pt FFT, sampling frequency: 11 kHz, time resolution:

2.9 ms, Flat Top window).

If the frequency of interaction affects the structure of calls, subjects that interact

frequently with one another should produce calls that are more similar to each other. Thus,

members of the same party should have the greatest similarity, while members of the same

gang should produce calls that are more similar to each other than to calls produced by

members of another gang. If genetic relatedness affects the vocal structure, dyads that are

more highly related should reveal greater acoustic similarity. Note that these two effects

(interaction frequency and relatedness) are not mutually exclusive.

METHODS

We obtained recordings of grunts from a total of 27 male baboons in 2010/11, 2014, and

2016. Thirteen of the males were members of the 'Mare' gang and 14 were members of the

'Simenti' gang. The Mare gang comprised two parties of 6 and 7 males each; the Simenti

gang comprised two parties of 5 and 9 males each. Twenty-three of the 27 males were

confirmed or inferred to be present throughout the study period (see Electronic

Supplementary Material Tab. S1). We focused on grunt vocalizations given by males during

affiliative interactions with males and females (with or without infants); a previous analysis

did not reveal significant differences in relation to partner type (unpubl. data). Ideally, one

would have liked to include further groups with additional subjects to assess whether the

observed pattern holds across multiple groups, but this was beyond our capacities.

Vocalizations were recorded using Marantz PMD 661 recorders (D&M Professional,

Longford, U.K.) with Sennheiser directional microphones (K6 power module + ME66

recording head; Sennheiser, Wedemark, Germany) equipped with Rycote windshields

(RycoteWindjammer, Rycote Ltd., Stroud, U.K.). We used Avisoft SASLab Pro (Avisoft

Bioacoustic, Berlin, Germany) to check the recording quality and to label and extract grunts

with sufficient quality and low background noise. We only used calls recorded at a maximum

distance of 3 m. In total, we included 756 grunts in the acoustic analysis. On average, we

used 28 calls per subject in the analysis (range: 5-127). The Mare and Simenti gang males

were represented by 390 and 366 grunts, respectively.

We reduced the sampling frequency from 44.1 to 5 and 1 kHz to obtain an

appropriate frequency resolution for the estimation of acoustic features and calculated two

1024 pt Fast Fourier Transformation (FFT), one resulting in a frequency range of 2500 Hz

(frequency resolution 5 Hz, temporal resolution 6.4ms) and a second FFT resulting in a

frequency range of 500 Hz (frequency resolution of 1 Hz, and a temporal resolution of

16 ms). Calculating two FFTs allowed us to maximize the temporal resolution for the entire

call type, and estimate the fundamental frequency at a higher frequency resolution. The

resulting frequency-time spectra were analyzed with a custom software program LMA 2019,

which allows visual control of the accuracy of parameter estimation [20,21]. LMA outputs a

total of 82 acoustic parameters.

To identify which parameters would be informative to distinguish between individuals

(and thus, social levels), we entered all 82 acoustic features from the LMA output into a

stepwise discriminant function (DFA) with subject identity as a grouping variable. The

selection criterion for acoustic features to enter the discriminant function was P_{in} = 0.05 and

to remove P_{out} = 0.1. The DFA used 31 acoustic features for individual discrimination

(Electronic Supplementary Material Tab. S2). To quantify the acoustic variation between

males, we used the average pairwise F-value from the discriminant function analysis as a

dissimilarity score for each dyad. This approach has been applied in different studies

examining relationships between acoustic structure and genetic or geographic distance

[22,23]. The discriminant function analysis was performed using IBM SPSS version 26.0

(IBM, Armonk, NY). To assess whether the classification result of the individual

discrimination of male grunts is higher than would be expected by chance, we additionally

performed a permuted DFA [24], which controls for variation in individual contributions of

grunts.

We extracted DNA from fecal samples using the First-DNA all tissue kit (Genial®) and

characterized genetic variation by assessing the individual allele variation on 24 polymorphic

autosomal microsatellite markers. The 24 markers were amplified using the Multiplex PCR

Kit (QIAGEN) and fluorescent-labelled primers. PCR products were separated and detected

through capillary gel electrophoresis on an ABI 3130xL Genetic Analyzer (Applied

Biosystems®, USA). Microsatellite allele sizes were evaluated using Gene Mapper 5

(Applied Biosystems®). One locus (D1s548) showed signs of null alleles and significant

deviations from Hardy-Weinberg equilibrium and was therefore excluded, resulting in a total

of 23 loci included in the relatedness estimation (calculated with MICRO-CHECKER version

2.2.3 [25] and the PopGenReport R package version 3.0.0 [26]. We used the R package

"related" version 1.0 [27,28] to estimate relatedness using R version 3.4.4 and RStudio

version 1.1.456. The Wang estimator W showed the best performance and was thus chosen

in the present analysis. W ranges from -1 to 1. Negative values indicate that dyads are less

related than on average, while positive values indicate that they are more highly related than

on average [see 29 for a detailed description of the analysis].

These and the following statistical analyses were conducted in the R environment

version 3.6.3 [30], using the RStudio interface version 1.3.959 [31]. We used a mantel matrix

correlation test (package "vegan"; version 2.5.6) to test the correlation between acoustic and

genetic variation. To test whether calls a gang were more similar to each other than between

gangs, we applied a categorical mantel test, using 'same gang membership' (Yes/No) as the

categorical predictor variable, and W or F (transformed as ln(1+F)) as the continuous

variable. The analysis of the effect of gang membership was based on 351 dyads. To study

the effect of party membership, we also used a categorical mantel test, but only considered

pairs of males that lived in the same gang (e.g., ADM and ASN, both members of the Mare

gang, or BEN and WLD, both members of the Simenti gang; total number of dyads within

both gangs N = 169). We used a restricted permutation approach where males were

permuted between parties within gangs. We used 1,000 permutations in all analyses, except

the one for the variation between parties within gangs, where we used 10,000 permutations.

Effect sizes were calculated with the package "effsize" version 0.8.0. The data and code for

statistical analysis are deposited at

https://osf.io/h7q5r/?view_only=e24fb7b53e7a4c57a1fe67db5d2452ab.

ETHICS STATEMENT

This research complies with the Association for the Study of Animal Behaviour Guidelines for

the Use of Animals in Research (Animal Behaviour, 2018, 135, I-X), the legal requirements of

the country in which the work was carried out, and all institutional guidelines. The research

has been approved by the Direction des Parcs Nationaux of the Republic of Senegal

(22/04/19).

RESULTS

Confirming previous analyses, males were more highly related within gangs than between

gangs (Categorical Mantel Test, $P = 0.001$, $N = 351$, Figure 2a). The effect size (Cohen's d)

was 0.52 (CI_{lower} -0.73, CI_{upper} -0.31; medium effect size). Within gangs, males in the same

party were more highly related on average than males that were not members of the same

party ($P = 0.035$, $N = 169$, Figure 2b), with a small effect size ($d = 0.24$, CI_{lower} -0.54, CI_{upper} -

0.07).

Figure 2. Genetic relatedness between male dyads that belong to (a) different gangs or the

same gang, and (b) different parties or the same party within a gang. Light grey dots

represent dyadic values, black dots the mean with 95% confidence interval.

Grunts could be assigned to the correct individual significantly more frequently than

by chance, with an average correct assignment of 34.5 % using the procedure in SPSS

(chance level 3.7%, leave-one-out validation: 21.0 % correct classification). The classification

in the pDFA with a reduced set of N=135 calls (see Electronic Supplementary Material Tab.

S3 yielded an average classification of 11.2%, $P < 0.001$). Acoustic similarity did not

correlate with genetic similarity ($r = -0.006$, $P = 0.515$). Because of the inherent uncertainty

with which dyadic relatedness can be estimated [32], we ran an additional analysis in which

we compared the acoustic dissimilarity of dyads in the top quartile ($W > 0.125$) vs. the bottom

quartile ($W < -0.117$). Again, we found no effect of relatedness on acoustic dissimilarity

(categorical Mantel test, $P = 0.933$, Fig. 3).

Figure 3. Relation between acoustic dissimilarity and genetic relatedness (top and bottom

quartiles of the Wang estimator W) for N = 175 dyads. Light grey dots represent dyadic

values, black dots the mean with 95% confidence interval. There were no significant

differences between unrelated and related individuals (P = 0.933).

Grunts of males within gangs were more similar to each other than between gangs

(categorical Mantel test, P = 0.012, Fig. 4a), and grunts of males within a party were also

more similar to each other than between parties in the same gang (P = 0.001, Fig. 4b). The

effect sizes were modest, however (d = 0.177, CI_{lower} -0.03, CI_{upper} 0.38 between gangs and

0.152, CI_{lower} -0.15, CI_{upper} 0.46 between parties, respectively). When we compared the mean

acoustic dissimilarity of males that resided in the same party (mean logF = 0.29) to those that

were part of a different gang (mean logF = 0.33), the effect size was small (d = 0.24, CI_{lower} -

0.02, CI_{upper} 0.50). Grunts varied with social level (party/gang) mostly in parameters that are

related to articulatory movements (Electronic Supplementary Material Tab. S4). The

fundamental frequency or duration did not vary systematically between social levels.

Figure 4. Acoustic dissimilarity of dyads that belong to (a) different gangs or the same gang,

and (b) different parties or the same party within a gang. Light grey dots represent dyadic

values, black dots the mean with 95% confidence interval. Calls from males in the same

gang and the same party were on average more similar to each other than between gangs or

parties.

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DISCUSSION

The structure of male grunts varied between members of different gangs, and also between

members of parties within a gang. The effect sizes of these two comparisons were modest,

however. Males in the same gang were also more highly related to one another, but this did

not account for the acoustic variation between parties and gangs, as evidenced by the lack of

an effect of genetic relatedness on acoustic similarity. In this regard, the Guinea baboons

differ from mandrills, where both relatedness and interaction frequency predicted the

structure of the vocalizations [15].

It may seem puzzling at first that genetic relatedness did not account for the higher

vocal similarity in Guinea baboons despite the fact that genetic relatedness and acoustic

similarity were both higher within parties and gangs than between. This can be explained by

a combination of the fact that not all dyads within a social level are indeed more highly

related than across these social levels, and that acoustic similarity appears mainly to be

driven by social interaction, which is not restricted to highly related dyads. To a certain

degree, relatedness and acoustic similarity vary independently of one another.

How may auditory input affect vocal production? One mechanism that may support

the reported minor adjustments in vocal output with experience may rest on sensory-motor

integration [33]. According to the idea of a 'common coding' framework, specific sensorimotor

areas represent both sensory input and motor commands generating that corresponding

pattern [34]. In humans, neuroimaging studies identified specific motor activations when

subjects listened to speech sounds [35]. If such sensory-motor integration exists in the

auditory-vocal domain of nonhuman primates, the exposure to specific auditory input may

increase the likelihood to produce the corresponding motor pattern via co-activation.

A recent study provided compelling evidence for the integration of auditory input with

vocal output in a nonhuman primate species. In common marmosets, activity in the auditory

cortex directly affected the monkeys' control of vocal production [36]. Firstly, a shift in the

auditory feedback of the monkey's vocalization led to compensatory changes in the

frequency patterns of the subsequent vocalizations. Secondly, microstimulation of the

auditory cortex during vocalization led to abrupt shifts in vocal frequency [36]. In a

translocation experiment, common marmosets (N = 4) adjusted the structure of their

vocalizations in response to auditory input from conspecifics, even if the individuals do not

interact directly [37]. Beyond the immediate effects of auditory experience, there is also

evidence that feedback from parents affects the trajectory of vocal development in

marmosets [38–40].

It has been argued that the human ability to imitate the utterances of others gradually

evolved from the vocal plasticity observed in nonhuman primates [17,41]. We contend that

vocal learning may be based on a variety of different mechanisms, including vocal

convergence, 'learning from success', a form of usage learning that comprises the use of

specific call variants because they are more likely to yield the desired response, as well as

the spontaneous imitation of a recently formed auditory template [42]. Instead of conceiving

vocal learning capacities as a continuum [43], we agree with other authors that vocal learning

may be supported by a variety of different mechanisms [44]. Future studies should aim to

distinguish between these mechanisms, and also consider the effect size of vocal plasticity.

Taking the extent of plasticity as well as the mechanisms that support them into

account will contribute to overcoming futile debates about whether or not nonhuman primates

reveal evidence for vocal learning [45]. The vast majority of studies in nonhuman primates

that reported evidence for vocal convergence observed only minor changes within the

species-specific range of calls. Thus, the small effect sizes reported here are an important

aspect of the results. Humans, instead, are not only able to work on their accents, as Eliza

Doolittle in 'My fair lady', but they can also sing "supercalifragilisticexpialidocious" with Mary

Poppins. The spontaneous imitation of new words is open-ended, while it is much more

difficult to change one's accent once a certain age has been reached. Vocal convergence in

nonhuman primates appears to be more similar to the formation of an accent than the

acquisition of novel phonetic combinations that make up new words. An interesting open

question is whether vocal convergence is simply a by-product of the sensory experience or

whether it has been selected for, since it may signal 'in-group' membership and thus have an

important social function [46].

Irrespective of whether vocal convergence has been selected for or not, we propose

that it constitutes an implicit form of motor learning shared between nonhuman primates and

humans, while speech production constitutes an explicit form of motor learning. Implicit and

explicit processes are not entirely dichotomous; explicitly acquired motor skills can become

automatic (as when you learn to drive a car), while implicit processes may be made explicit

[47]. Yet, it has proven useful to distinguish between implicit and explicit forms of knowledge

and knowledge acquisition [48]. Taatgen suggested that implicit learning is a by-product of

general learning mechanisms, while explicit learning is tied to learning goals and thus

intentionality [47]. This definition appears useful for the distinction between vocal

convergence as a result of sensory-motor integration on the one hand and the goal-directed

acquisition of the patterns that result in the production of speech, on the other.

A further open question is whether the observed acoustic variation is salient to the

animals themselves. In a previous study [49], we tested male responses to the playbacks of

grunts of males that share the same home range as the study males ("neighbours") vs. to

grunts of males living 50 km away ("strangers"). As a control, we played back the grunts of

males from their gang. Surprisingly, males responded strongly only to the grunts from males

of their gang, but largely ignored neighbour or stranger males' calls. In principle, these

responses could be explained by the recognition of the males' characteristics. Yet, it might

also be the case that males recognize the 'sound' of their subgroup. Playbacks presenting

artificially created grunts bearing the own gang's characteristics vs. another gang's

characteristics would be needed to test this conjecture.

In summary, we find evidence for a moderate degree of vocal convergence in the

grunts of male Guinea baboons. The magnitude of the change is difficult to compare to those

of other studies on nonhuman primates mentioned above, given the differences in

methodological approaches, but broadly appears to be in a similar range. Our findings add to

the body of evidence that within species-specific constraints, subtle and potentially

meaningful variation can be found in nonhuman primate vocalizations. This variation does

not compare to the open-ended possibility of vocal imitation found in human speech,

however.

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Author contributions

JF, KH, and FW conceived the study, FW collected the data, FW and KH conducted the

acoustic analysis, FDP and FT conducted the genetic analysis, JF and KH ran the statistical

analyses and prepared the figures, JF wrote the manuscript with input from all authors.

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