Rhesus monkeys (Macaca mulatta) detect rhythmic groups in music, but not the beat

Honing, H.; Merchant, H.; Háden, G.P.; Prado, L.; Bartolo, R.

Published in:
PLoS ONE

DOI:
10.1371/journal.pone.0051369

Citation for published version (APA):
https://doi.org/10.1371/journal.pone.0051369

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Rhesus Monkeys (Macaca mulatta) Detect Rhythmic Groups in Music, but Not the Beat

Henkjan Honing1*, Hugo Merchant2, Gábor P. Háden1, Luis Prado2, Ramón Bartolo2

1 Cognitive Science Center Amsterdam, Institute for Logic, Language and Computation, University of Amsterdam, Amsterdam, The Netherlands, 2Department of Cognitive Neuroscience, Instituto de Neurobiología, Universidad Nacional Autónoma de México, Campus Juriquila, Querétaro, México

Abstract

It was recently shown that rhythmic entrainment, long considered a human-specific mechanism, can be demonstrated in a selected group of bird species, and, somewhat surprisingly, not in more closely related species such as nonhuman primates. This observation supports the vocal learning hypothesis that suggests rhythmic entrainment to be a by-product of the vocal learning mechanisms that are shared by several bird and mammal species, including humans, but that are only weakly developed, or missing entirely, in nonhuman primates. To test this hypothesis we measured auditory event-related potentials (ERPs) in two rhesus monkeys (Macaca mulatta), probing a well-documented component in humans, the mismatch negativity (MMN) to study rhythmic expectation. We demonstrate for the first time in rhesus monkeys that, in response to infrequent deviants in pitch that were presented in a continuous sound stream using an oddball paradigm, a comparable ERP component can be detected with negative deflections in early latencies (Experiment 1). Subsequently we tested whether rhesus monkeys can detect gaps (omissions at random positions in the sound stream; Experiment 2) and, using more complex stimuli, also the beat (omissions at the first position of a musical unit, i.e. the ‘downbeat’; Experiment 3). In contrast to what has been shown in human adults and newborns (using identical stimuli and experimental paradigm), the results suggest that rhesus monkeys are not able to detect the beat in music. These findings are in support of the hypothesis that beat induction (the cognitive mechanism that supports the perception of a regular pulse from a varying rhythm) is species-specific and absent in nonhuman primates. In addition, the findings support the auditory timing dissociation hypothesis, with rhesus monkeys being sensitive to rhythmic grouping (detecting the start of a rhythmic group), but not to the induced beat (detecting a regularity from a varying rhythm).

Introduction

The ability to perceive a regular beat in music and synchronize to it (e.g., by foot tapping or dancing) is a common and widespread human skill [1]. It is also a skill that has been suggested to be domain-specific [2] and, arguably, conditional to the origins of music [3]. Nevertheless, it is still unclear whether this ability should be considered species-specific [4]. It was recently shown that rhythmic entrainment, long considered a human-specific mechanism, can be demonstrated in a select group of bird species [5,6], and, somewhat surprisingly, not in more closely related species such as nonhuman primates [7]. This observation supports the vocal learning hypothesis [8] that suggests that rhythmic entrainment is a by-product of the vocal learning mechanisms that are shared by several bird and mammal species, including humans, but that are only weakly developed, or missing entirely, in nonhuman primates [4]. However, since no evidence of rhythmic entrainment was found in many vocal learners (including dolphins, seals, and songbirds [9]), vocal learning may be necessary, but not sufficient [4] for beat induction – the cognitive mechanism that supports the perception of a regular pulse from a varying rhythm [3].

In addition, there might be a dissociation between rhythm perception and beat induction, as was shown in a lesion study with humans [10]. This study suggests different cognitive mechanisms to be active for duration-based timing versus beat-based timing, with beat induction being dependent on distinct parts of the timing network in the brain [11,12]. We hypothesize that humans share rhythm perception (or duration-based timing) with other primates, while the beat induction (or beat-based timing) is only present in specific species (including humans and a selected group of bird species [6]), arguably as a result of convergent evolution [13]. We will refer to this as the auditory timing dissociation hypothesis.

Most existing animal studies on rhythmic entrainment have used behavioral methods to probe the presence of beat perception, such as tapping tasks [7] or measuring head bobs [5]. However, if the production of synchronized movement to sound or music is not observed in certain species (such as in nonhuman primates, seals or dolphins [9]), this is no evidence for the absence of beat perception. It could well be that while certain species are not able to synchronize movements to a rhythm, they do have beat induction and as such, can perceive a beat. With behavioral methods that rely on overt motoric responses it is difficult to
separate between the contribution of perception and action; more
direct, electrophysiological measures such as event-related brain
potentials, allow testing for neural correlates of beat perception.

In the current study, we measure auditory event-related brain
potentials (ERP) in two rhesus monkeys (Macaca mulatta) using the
mismatch negativity component (MMN) as an index of the
violation of rhythmic expectation using an oddball paradigm
[3,14]. MMN has been investigated mainly in mice, rats and rodents
(which are primarily negative), and in carnivores (cat) and primates
(macaque), which have reported positive results. Most studies,
however, use intracranial and single-cell recording techniques and
measure stimulus-specific adaptation (SSA), an index that is similar
but not identical to MMN [see [15] for a discussion]. Just a few
studies measured non-invasive scalp-recorded auditory event-
related potentials (ERPs) in nonhuman primates, with Ueno et al.
[16] being the first study, to our knowledge, to show it is possible, in
principle, to measure an MMN-like response in an awake, non-
sedated chimpanzee (Pan troglodytes).

In the current study, using oddball paradigms [3,14], we record
auditory ERPs from two rhesus monkeys (Macaca mulatta) utilizing
the MMN as an index of the violation of (rhythmic) expectation.
First we tested whether an MMN can be elicited in rhesus
monkeys (using deviant tones at random positions in the sound
stream; Experiment 1). Second, we investigated whether an MMN
can be elicited by infrequent omissions of regular tones (inserting
gaps at random positions in the sound stream; Experiment 2).
Subsequently, we probed the presence of beat induction by
selectively omitting parts of a musical rhythm (randomly inserting
gaps at the first position of a musical unit, i.e. the ‘downbeat’;
Experiment 3).

The latter paradigm has been used previously to show sensitivity
to the beat in human adults and newborns [17,18,19,20]. In these
studies sound sequences were used that are based on a typical 2-
measure rock drum accompaniment pattern composed of snare,
bass and hi-hat spanning 8 equally spaced (isochronous) positions
(see Figure 1). Because the MMN is known to be elicited by
deviations from temporal expectations [3], it is especially
appropriate for testing beat induction. One of the most salient
perceptual effects of beat induction is a strong expectation of an
event at the first position of a musical unit, i.e., the ‘downbeat’.
Therefore, occasionally omitting the downbeat in a sound
sequence composed predominantly of strictly metrical (regular or
‘nonsyncopated’) variants of the same rhythm should elicit
discriminative ERP responses, that is, if the subject extracted the
beat of the sequence.

Methods

Ethics Statement

All the animal care, housing, experimental procedures were
approved by the National University of Mexico Institutional
Animal Care and Use Committee and conformed to the principles
outlined in the Guide for Care and Use of Laboratory Animals
(NIH, publication number 85-23, revised 1985). Both monkeys
were monitored daily by the researchers and the animal care staff,
and every second day from the veterinarian, to check the
conditions of health and welfare. To ameliorate their condition
of life we routinely introduced in the home cage (1.3 m³)
environment toys (often containing items of food that they liked) to
promote their exploratory behavior. The researcher that tested the
animals spent half an hour interacting with the monkeys directly,
giving for example new objects to manipulate. We think that this
interaction with humans, in addition to the interaction that was
part of the task performed, can help to reduce potential stress
related to the experiment. Food and water where given ad libitum.

Participants

Two rhesus monkeys participated in the ERP measurements. Aji, a 2 year old male (referred to as monkey A) and Yko, a 5 year
old male (referred to as monkey Y). Both monkeys have normal
hearing. They were awake (i.e. not sedated) during the measure-
ments, sitting in a quiet room [3 (b)×2 (d)×2.5 (h) m] with dimmed
lighting and two loudspeakers in front of them. The ERP
measurements were performed after a morning session of
unrelated behavioral experiments. The animals were seated
comfortably in a monkey chair where they could freely move
their hands and feet. No head fixation was used and the EEG
electrodes were attached to the monkey’s scalp using tape. To ease
the fixation of the electrodes, the monkey’s hair on the scalp and
reference ear was shaved.

Stimuli

In Experiment 1 pure sine-wave tones were used for the two-
stimulus oddball paradigm. Their frequencies were 500 Hz and
1500 Hz, with a duration of 50 ms, and a rise and fall of 5 ms.
The frequencies of these tones were within the audible range of
both monkeys.

In Experiment 2 a sine-wave with a frequency 1000 Hz was
used, with a duration of 50 ms and a rise and fall of 5 ms.
In Experiment 3 sound sequences based on a typical 2-measure
rock drum accompaniment pattern (S1) were used, composed of
snare, bass and hi-hat, spanning equally spaced positions (see
Figure 1). Four further variants of the S1 pattern (S2-S4 and D)
were created by omitting sounds in different positions. Within the
patterns the onset-to-onset interval between successive sounds was
150 ms with 75 ms on-set-to-offset interval (75 ms sound duration).
Patterns in the sequence were delivered as a continuous sound
stream. Loudness of the sounds was normalized so that all stimuli
had the same loudness.

Sound stimuli were presented through 2 loudspeakers placed 1.1
meters away from the subject (and 1 meter apart from each other).
The sound intensity measured at the subject position was
approximately 60 dB SPL.

Procedures/Experimental Design

In all three experiments an auditory oddball paradigm was
used. The experimental paradigm was adapted from previous
studies (Experiment 1: [16]; Experiment 2: [21]; Experiment 3:
[20]).

In Experiment 1 and 2 sound inter-onset-intervals were 600 ms
and 150 ms, respectively. In both experiments standards (0.9
probability) were randomly replaced (0.1 probability) with deviants
and deviant omissions (i.e. silence), respectively. In Experiment 1 for
half of the blocks one frequency was used as deviant and the other as
standard (i.e. S500-D1500), switching roles for the other half of the
blocks (i.e. S1500-D500). In Experiment 2 the inter-onset-interval was
150 ms (an interval motivated by human studies [21], and that is
within the ‘preferred tempo’ range of rhesus monkeys [22]).

In Experiment 3 the 4 strictly metrical sound patterns (S1–S4;
standards) made up the majority of the patterns in the sequences
(0.225 probability, respectively). In the standard patterns regular
omissions occurred in metrically weak positions, leaving these
patterns metrically intact. Occasionally, the D pattern was
delivered (0.1 probability) in which the downbeat was omitted,
which interrupted the metricality of the pattern. The order of the
color patterns was pseudo-randomized, enforcing at least three
standard patterns between successive D patterns and no D after S1.
to avoid two consecutive omissions. A control sequence (deviant-control) repeating the D pattern 100% of the time was also delivered (see [20] for more details).

The ERP measurements were conducted in a repeated session, containing all three experiments in random order. The monkeys participated in one recording session per day, to a total of 11 sessions for monkey A and 23 sessions for monkey Y (monkey Y moved considerably more than Monkey A). All measurement was completed in about one month per monkey. Each experiment consisted of 10 blocks with 306 repetitions for each block.

**EEG Recording and Analysis**

The EEG was recorded from electrodes (Grass EEG electrodes; #FS-E5GH-60) attached to five scalp positions (Fz, Cz, Pz, F3, F4) according to the 10–20 system (see Figure 2).

The electrodes were connected to a Tucker-Davis Technologies (TDT) headstage (#RA16LI) for low impedance electrodes. This
headstage was connected to a TDT RA16PA preamplifier, which in turn was connected to a TDT RZ2 processor. RZ2 was programmed to acquire the EEG signals with a sampling rate of 498.25 Hz and the bandpass filters were set at 0.01–100 Hz.

All electrodes were attached using Ten20 Conductive EEG Paste and medical tape, and were referenced to the right ear (fleshy part of the pinna). In the offline analysis, a 0.1–30 Hz bandpass FIR filter (Kaiser-window) was applied. With zero latency set to the onset of the stimuli, epochs of −100–500 ms (Experiment 1), 0–450 ms (Experiment 2), and 0–600 ms (Experiment 3) were extracted. All epochs were baseline corrected to zero using a 100 ms pre-stimulus interval in Experiment 1 and the whole epoch in Experiments 2 and 3. Epochs that exceeded +/-150 μV amplitude were excluded from the statistical analysis. EMG recordings were obtained from the temporalis muscles. No event-locked activity was found in these recordings. The number of epochs accepted for analysis for the three experiments are given in the Tables 1–4.

Statistical analysis was performed on the mean amplitudes in a 50 ms wide time window centered on the absolute maximum peak of difference waveforms (i.e. the difference between the standard and deviant wave). The resulting windows are stated underneath the Tables 1 to 4 and marked with gray-shaded rectangles in Figures 3, 4, 5. In all three experiments channel Cz was used for the latency measurements.

The resulting values were fed into an analysis of variance (ANOVA), where Electrode sites were treated as a within subject variable and all other variables as grouping variables. For Experiment 1 factors Stimulus (500 Hz vs. 1500 Hz) × Type (Deviant vs. Standard) × Electrode (Fz vs. Cz vs. Pz vs. F3 vs. F4) were used, for Experiment 2 Type (Omission vs. Sound) × Electrode (Fz vs. Cz vs. Pz vs. F3 vs. F4), and for Experiment 3 Type (Deviant vs. Deviant control vs. S1 vs. 4) × Electrode (Fz vs. Cz vs. Pz vs. F3 vs. F4). Greenhouse-Geisser correction was used where necessary (corrected p, df and epsilon values reported).

Table 1. Mean amplitudes of standard- and deviant-waves for each condition and scalp position (Experiment 1).

<table>
<thead>
<tr>
<th>Monkey A</th>
<th>S1500 (n = 21834)</th>
<th>D1500 (n = 2219)</th>
<th>S2000 (n = 20993)</th>
<th>D2000 (n = 2353)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fz</td>
<td>−2.0 (0.2)</td>
<td>−8.2 (0.5)</td>
<td>−2.6 (0.2)</td>
<td>−4.7 (0.5)</td>
</tr>
<tr>
<td>Cz</td>
<td>−1.2 (0.1)</td>
<td>−5.1 (0.5)</td>
<td>−1.7 (0.1)</td>
<td>−3.4 (0.4)</td>
</tr>
<tr>
<td>Pz</td>
<td>−0.3 (0.1)</td>
<td>−0.6 (0.5)</td>
<td>−0.8 (0.1)</td>
<td>−0.7 (0.4)</td>
</tr>
<tr>
<td>F3</td>
<td>−1.7 (0.1)</td>
<td>−6.4 (0.5)</td>
<td>−2.3 (0.1)</td>
<td>−3.7 (0.4)</td>
</tr>
<tr>
<td>F4</td>
<td>−1.4 (0.1)</td>
<td>−6.0 (0.5)</td>
<td>−1.9 (0.2)</td>
<td>−4.0 (0.4)</td>
</tr>
</tbody>
</table>

Table 2. Mean amplitudes of standard- and deviant-waves for each scalp position (Experiment 2).

<table>
<thead>
<tr>
<th>Monkey A</th>
<th>S (n = 13187)</th>
<th>D (n = 2523)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fz</td>
<td>3.2 (0.2)</td>
<td>1.5 (0.3)</td>
</tr>
<tr>
<td>Cz</td>
<td>2.5 (0.2)</td>
<td>1.1 (0.4)</td>
</tr>
<tr>
<td>Pz</td>
<td>0.6 (0.2)</td>
<td>−0.2 (0.3)</td>
</tr>
<tr>
<td>F3</td>
<td>2.5 (0.1)</td>
<td>0.8 (0.3)</td>
</tr>
<tr>
<td>F4</td>
<td>2.6 (0.1)</td>
<td>0.7 (0.3)</td>
</tr>
</tbody>
</table>

Table 3. Mean amplitudes of standard- and deviant-waves for each condition and scalp position (Experiment 3).

<table>
<thead>
<tr>
<th>Monkey A</th>
<th>S1500 (n = 35613)</th>
<th>D1500 (n = 33578)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fz</td>
<td>−3.0 (0.1)</td>
<td>−7.6 (0.3)</td>
</tr>
<tr>
<td>Cz</td>
<td>−3.7 (0.1)</td>
<td>−7.3 (0.4)</td>
</tr>
<tr>
<td>Pz</td>
<td>−1.0 (0.2)</td>
<td>−1.0 (0.5)</td>
</tr>
<tr>
<td>F3</td>
<td>−2.2 (0.1)</td>
<td>−4.7 (0.4)</td>
</tr>
<tr>
<td>F4</td>
<td>−1.8 (0.1)</td>
<td>−5.1 (0.4)</td>
</tr>
</tbody>
</table>

Table 4. Mean amplitudes of standard- and deviant-waves for each condition and scalp position (Experiment 3).

<table>
<thead>
<tr>
<th>Monkey A</th>
<th>S (n = 22907)</th>
<th>D (n = 4458)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fz</td>
<td>−0.8 (0.1)</td>
<td>−0.1 (0.2)</td>
</tr>
<tr>
<td>Cz</td>
<td>−1.1 (0.1)</td>
<td>0.0 (0.3)</td>
</tr>
<tr>
<td>Pz</td>
<td>−1.3 (0.2)</td>
<td>−0.8 (0.3)</td>
</tr>
<tr>
<td>F3</td>
<td>−0.5 (0.1)</td>
<td>−0.2 (0.3)</td>
</tr>
<tr>
<td>F4</td>
<td>−0.2 (0.1)</td>
<td>0.2 (0.3)</td>
</tr>
</tbody>
</table>

Note. Mean amplitudes (μV) are indicated with SE values in parentheses. S: values for standard stimuli; D: values for deviant stimuli; Subscript indicates tone frequency in Hz; number of epochs (n) are indicated in parentheses. The time windows adopted are 59–109 ms for monkey A and 61–111 ms for monkey Y (See Methods).
Table 3. Mean amplitudes of standard- (S₁–₄), deviant- (D), and ‘deviant-control’-waves (Dcontrol) in the early window (just after the omission) for each stimulus type and scalp position (Experiment 3).

<table>
<thead>
<tr>
<th>Monkey A</th>
<th>S₁ (n = 5458)</th>
<th>S₂ (n = 5518)</th>
<th>S₃ (n = 5515)</th>
<th>S₄ (n = 5421)</th>
<th>D (n = 2404)</th>
<th>Dcontrol (n = 12959)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fz</td>
<td>-0.2 (0.2)</td>
<td>0.2 (0.2)</td>
<td>0.2 (0.2)</td>
<td>0.2 (0.2)</td>
<td>0.3 (0.3)</td>
<td>-0.1 (0.1)</td>
</tr>
<tr>
<td>Cz</td>
<td>-1.8 (0.2)</td>
<td>0.4 (0.2)</td>
<td>-1.3 (0.2)</td>
<td>-1.3 (0.2)</td>
<td>1.8 (0.4)</td>
<td>-2.6 (0.1)</td>
</tr>
<tr>
<td>Pz</td>
<td>-1.3 (0.2)</td>
<td>1.2 (0.2)</td>
<td>-1.3 (0.2)</td>
<td>-1.1 (0.2)</td>
<td>1.5 (0.4)</td>
<td>-0.9 (0.1)</td>
</tr>
<tr>
<td>F3</td>
<td>-1.6 (0.2)</td>
<td>0.7 (0.2)</td>
<td>-1.2 (0.2)</td>
<td>-0.3 (0.2)</td>
<td>1.8 (0.3)</td>
<td>-2.3 (0.1)</td>
</tr>
<tr>
<td>F4</td>
<td>-1.7 (0.2)</td>
<td>0.0 (0.2)</td>
<td>-1.1 (0.2)</td>
<td>-0.6 (0.2)</td>
<td>1.7 (0.3)</td>
<td>-2.0 (0.1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Monkey Y</th>
<th>S₁ (n = 9865)</th>
<th>S₂ (n = 9791)</th>
<th>S₃ (n = 9862)</th>
<th>S₄ (n = 9833)</th>
<th>D (n = 4272)</th>
<th>Dcontrol (n = 5454)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fz</td>
<td>-3.1 (0.2)</td>
<td>-1.8 (0.2)</td>
<td>-0.8 (0.2)</td>
<td>-0.4 (0.2)</td>
<td>-3.9 (0.2)</td>
<td>-0.3 (0.2)</td>
</tr>
<tr>
<td>Cz</td>
<td>-3.3 (0.2)</td>
<td>-2.4 (0.2)</td>
<td>-1.8 (0.2)</td>
<td>-1.0 (0.2)</td>
<td>-5.3 (0.3)</td>
<td>-0.8 (0.3)</td>
</tr>
<tr>
<td>Pz</td>
<td>-3.4 (0.2)</td>
<td>-2.0 (0.3)</td>
<td>-2.8 (0.3)</td>
<td>-1.8 (0.2)</td>
<td>-2.9 (0.4)</td>
<td>-0.4 (0.4)</td>
</tr>
<tr>
<td>F3</td>
<td>-2.6 (0.2)</td>
<td>-1.6 (0.2)</td>
<td>-0.8 (0.2)</td>
<td>-0.9 (0.2)</td>
<td>-2.9 (0.3)</td>
<td>-0.4 (0.2)</td>
</tr>
<tr>
<td>F4</td>
<td>-2.4 (0.2)</td>
<td>-1.3 (0.2)</td>
<td>-0.9 (0.2)</td>
<td>-0.3 (0.2)</td>
<td>-2.9 (0.3)</td>
<td>-0.3 (0.2)</td>
</tr>
</tbody>
</table>

Note. Mean amplitudes (µV) are indicated with SE values in parentheses. S₁–₄: values for standard stimuli; D: values for deviant stimuli; Dcontrol: Values for deviant-control stimuli; n: number of epochs. The time windows adopted are 105–155 ms for monkey A and 73–123 ms for monkey Y (See Methods).

doi:10.1371/journal.pone.0051369.t003

doi:10.1371/journal.pone.0051369.t004

Results

Pitch Deviants Evoke an MMN-like Response

In Experiment 1 we presented two rhesus monkeys with a sequence of sounds using a two-tone oddball paradigm (see Methods) to see whether an MMN-like response can be elicited.

Figure 3 shows that the electrical brain responses elicited by the standard and deviant stimulus are different for both monkeys, with a morphology comparable to a human MMN, though with a shorter latency (peaks around 90 ms, instead of 150 ms) and slightly larger amplitude as compared to humans (around 10 µV, instead of 5 µV) [23]. These differences in latency and amplitude can be attributed to the anatomical differences between human and monkey brains (e.g., skull size, thickness, and the distribution of musculature [24]).

For monkey A the ANOVA with factors Stimulus (500 Hz vs. 1500 Hz) × Type (Deviant vs. Standard) × Electrode (Fz vs. Cz vs. Pz vs. F3 vs. F4) revealed significant main effects in Type (F(1,

Table 4. Mean amplitudes of standard- (S₁–₄), deviant- (D), and ‘deviant-control’-waves (Dcontrol) in the late window (just after the first sound) for each stimulus type and scalp position (Experiment 3).

<table>
<thead>
<tr>
<th>Monkey A</th>
<th>S₁ (n = 5458)</th>
<th>S₂ (n = 5518)</th>
<th>S₃ (n = 5515)</th>
<th>S₄ (n = 5421)</th>
<th>D (n = 2404)</th>
<th>Dcontrol (n = 12959)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fz</td>
<td>-0.6 (0.2)</td>
<td>-2.8 (0.2)</td>
<td>-0.9 (0.2)</td>
<td>-0.7 (0.2)</td>
<td>-0.8 (0.4)</td>
<td>-5.0 (0.1)</td>
</tr>
<tr>
<td>Cz</td>
<td>-0.8 (0.2)</td>
<td>-2.2 (0.2)</td>
<td>-0.1 (0.2)</td>
<td>-0.7 (0.2)</td>
<td>-1.0 (0.4)</td>
<td>-3.1 (0.1)</td>
</tr>
<tr>
<td>Pz</td>
<td>-0.2 (0.2)</td>
<td>-1.6 (0.2)</td>
<td>-0.6 (0.2)</td>
<td>-0.3 (0.2)</td>
<td>-0.4 (0.4)</td>
<td>-1.0 (0.1)</td>
</tr>
<tr>
<td>F3</td>
<td>-0.6 (0.2)</td>
<td>-2.4 (0.2)</td>
<td>-0.8 (0.2)</td>
<td>-1.1 (0.2)</td>
<td>-0.9 (0.3)</td>
<td>-4.0 (0.1)</td>
</tr>
<tr>
<td>F4</td>
<td>-0.7 (0.2)</td>
<td>-1.4 (0.2)</td>
<td>-0.4 (0.2)</td>
<td>-0.4 (0.2)</td>
<td>-0.8 (0.3)</td>
<td>-2.8 (0.1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Monkey Y</th>
<th>S₁ (n = 9865)</th>
<th>S₂ (n = 9791)</th>
<th>S₃ (n = 9862)</th>
<th>S₄ (n = 9833)</th>
<th>D (n = 4272)</th>
<th>Dcontrol (n = 5454)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fz</td>
<td>-1.9 (0.2)</td>
<td>-3.9 (0.2)</td>
<td>-3.9 (0.2)</td>
<td>-1.9 (0.2)</td>
<td>-1.9 (0.2)</td>
<td>-11.4 (0.3)</td>
</tr>
<tr>
<td>Cz</td>
<td>-2.4 (0.2)</td>
<td>-5.9 (0.2)</td>
<td>-5.8 (0.2)</td>
<td>-3.5 (0.2)</td>
<td>-2.8 (0.4)</td>
<td>-13.4 (0.4)</td>
</tr>
<tr>
<td>Pz</td>
<td>-1.5 (0.3)</td>
<td>-2.7 (0.3)</td>
<td>-2.8 (0.3)</td>
<td>-1.6 (0.3)</td>
<td>-2.3 (0.4)</td>
<td>-2.3 (0.4)</td>
</tr>
<tr>
<td>F3</td>
<td>-1.2 (0.2)</td>
<td>-2.5 (0.2)</td>
<td>-3.4 (0.2)</td>
<td>-1.4 (0.2)</td>
<td>-1.3 (0.3)</td>
<td>-6.9 (0.2)</td>
</tr>
<tr>
<td>F4</td>
<td>-1.2 (0.2)</td>
<td>-2.6 (0.2)</td>
<td>-2.7 (0.2)</td>
<td>-1.1 (0.2)</td>
<td>-1.6 (0.3)</td>
<td>-5.1 (0.2)</td>
</tr>
</tbody>
</table>

Note. Mean amplitudes (µV) are indicated with SE values in parentheses. S₁–₄: values for standard stimuli; D: values for deviant stimuli; Dcontrol: Values for deviant-control stimuli; n: number of epochs. The time windows adopted are 214–264 ms for monkey A and 220–270 ms for monkey Y (See Methods).

doi:10.1371/journal.pone.0051369.t004

doi:10.1371/journal.pone.0051369.t003
For monkey Y the mean negative amplitude for deviant stimuli was significantly greater than that for standard stimuli. An ANOVA with the same factors revealed significant main effects in Type ($F(1, 78644) = 206.474, P<0.001, \eta^2 = 0.003$) and Electrode ($F(3.236, 163892.2) = 181.928, P<0.0001, \eta^2 = 0.002, \epsilon = 0.584$). All interactions involving the Electrode factor were significant, namely Electrode × Stimulus × Type ($F(3.236, 163892.2) = 3.543, P<0.05, \eta^2 = 0.002, \epsilon = 0.584$), Electrode × Type ($F(2.336, 163892.2) = 35.920, P<0.0001, \eta^2 = 0.002, \epsilon = 0.584$) and Electrode × Stimulus × Type ($F(2.336, 163892.2) = 6.034, P<0.0001, \eta^2 = 0.003, \epsilon = 0.584$). Tukey unequal-N HSD post-hoc tests revealed no significant difference between F3 and F4 and Type having no effect on Pz. Additionally the effect of Type was only marginally significant ($df = 47395, P = 0.066$) on 1500 Hz stimuli.

For monkey Y the mean negative amplitude for deviant stimuli was significantly greater than that for standard stimuli. An ANOVA with the same factors revealed significant main effects in Type ($F(1, 151750.6) = 51.294, P<0.0001, \eta^2 = 0.001, \epsilon = 0.800$) and Electrode × Stimulus × Type ($F(3.202, 151750.6) = 104.555, P<0.001, \eta^2 = 0.002, \epsilon = 0.800$) as well as a Stimulus × Type interaction ($F(1, 47395) = 31.476, P<0.001, \eta^2 = 0.003$). All interactions involving the Electrode factor were significant, namely Electrode × Stimulus ($F(3.202, 151750.6) = 2.723, P<0.05, \eta^2 = 0.002, \epsilon = 0.800$), Electrode × Type ($F(3.202, 151750.6) = 51.294, P<0.0001, \eta^2 = 0.001, \epsilon = 0.800$) and Electrode × Stimulus × Type ($F(3.202, 151750.6) = 3.113, P<0.01, \eta^2 = 0.001, \epsilon = 0.800$). Tukey unequal-N HSD post-hoc tests revealed no difference between F3 and F4 and Type having no effect on Pz.

These results are in line with another study showing an MMN-like response in a single chimpanzee (Pan troglodytes) [16] using the same two-tone odd-ball paradigm with scalp-recorded EEG. Together with the current experiment these studies provide evidence that ERP and MMN can be measured in both monkeys and apes.

Omissions Evoke an MMN-like Response

To study whether an MMN can be elicited in response to omissions as well, the same rhesus monkeys were presented with a tone sequence in which tones were omitted (i.e. replaced by silence, see Methods).

Figure 3. Event-related potentials at Cz for Experiment 1. Zero-aligned ERP responses for standard (S500, S1500) and deviant (D500, D1500) tones for monkey A and monkey Y. Stimulus positions are marked with rectangles; The gray-shaded areas indicate the time windows used in the statistical analysis (See Table 1 for details on the time ranges used).
doi:10.1371/journal.pone.0051369.g003
Figure 4 shows the electrical brain responses elicited by the standard (S) and the deviant (D; an omission). (Note that Figure 4 shows a time window with three repetitions of the standard tone, marked by rectangles at either side of the time line.) This allows for a comparison of the responses to the first and second tone after the omission. To test the effects of the omission we concentrate on the time range closest to the occurrence of the omission (see Methods; Table 2). In both monkeys the standard stimuli elicit a steady-state response with increased amplitude, phase-aligned to the stimuli. The amplitude of the response for the first tone after the omission (see Figure 4), most notably in monkey Y, neural activity increased after the short period of silence, but returns near to previous levels by the second tone. This could also be interpreted as a response marking the beginning of a rhythmic group [25].

Mean amplitudes of responses elicited by standard and deviant stimuli were measured within a time window centered on the absolute maximum of the D minus S difference waves (see Table 2 and gray-shaded windows in Figure 4).

For monkey A an ANOVA with factors Type (Omission vs. Tone) × Electrode (Fz vs. Cz vs. Pz vs. F3 vs. F4) revealed significant main effects in Type \( (F(1, 15708) = 32.906, P<0.0001, \eta^2 = 0.002, \varepsilon = 0.724) \). Tukey unequal-N HSD post-hoc tests revealed no significant difference between F3 and F4.

For monkey Y an ANOVA with the same factors revealed significant main effects in Type \( (F(1, 27307) = 10.648, P<0.005, \eta^2<0.001) \) and Electrode \( (F(2.255, 61581.99) = 7.477, P<0.001, \eta^2<0.001, \varepsilon = 0.564) \). Tukey unequal-N HSD post-hoc tests revealed no significant difference between F3 and F4.

Again for both monkeys the average amplitude tended to be large in the frontal and central areas, without any laterality effects.

The ERP responses to the omission (red lines in Figure 4) have a morphology comparable to human MMN (i.e. negative in early latencies). However, the polarity of the responses, probably due to inter-individual differences, were different in the two monkeys. Nevertheless, there is a small, but significant amplitude difference between the standard tone and the omission in a time range comparable to human MMN [21,26] suggesting that the omission was indeed detected.
Rhesus Monkeys do not Detect ‘Loud Rests’, but are Sensitive to Rhythmic Grouping

In Experiment 3 we presented the same two rhesus monkeys with complex stimuli consisting of sound sequences based on a typical rock drum accompaniment pattern (see Figure 1). The standard stimuli are four randomly presented and strictly metrical sound patterns (S1–S4), with a deviant pattern (D) presented which the ‘downbeat’ omitted. Humans adults perceive the D pattern within the context of standards as if the rhythm was broken, stumbled, or became strongly syncopated for a moment [20]. We refer to the omission at the start of D as a ‘loud rest’ and the omissions in S2–S4 as ‘silent rests’; Music theory suggests the former to sound ‘syncopated’ (a violation of a metric expectation) and the latter not [3].

A sequence repeating the D pattern 100% of the time was also presented (‘deviant-control’ or Dcontrol) to allow controlling for acoustic effects on the ERP. On the basis of the dissociation hypothesis, and the observation that monkeys apparently can not synchronize to a beat [7] but are sensitive to auditory timing [12], one might expect that monkeys are sensitive to rhythmic structure (interval-based timing) but not to metric structure (beat-based timing). This hypothesis predicts that omissions that play a role in rhythmic grouping [27] can be detected, as they mark the structure of a rhythmic pattern (as is the case in Dcontrol), consequently not eliciting an MMN as they are part of the regularity. In contrast, the omissions that do not affect the rhythmic grouping will not be detected as part of a regularity, since they occur irregularly (as is the case in S2–S4 and D) and hence may elicit an MMN.

In humans these differences in salience appear to be related to the coding of an internal representation of the rhythmic structure of a sound pattern [27], with the first sound after a relatively long inter-onset interval determining the rhythmic group structure [25]. If this is the case we expect the first sound of a repeated rhythmic pattern (Dcontrol) – but not a randomly inserted pattern (D) – to elicit a response marking the beginning of a rhythmic group [25].

An alternative hypothesis is based on the observations made in human adults and newborns using the same stimuli and experimental paradigm [17,18,19,20]. This hypothesis predicts that primates are not only able to sense rhythmic grouping, but are also able to detect the regular beat that is induced by a varying rhythmic stimulus. The perception of a ‘loud rest’ – a violation of a temporal expectation reflected by an MMN-like signal – can serve as evidence for the presence of a strong metric expectation [3]. This hypothesis predicts an large and early MMN for the omission in the deviant (D, containing a ‘loud rest’), but no or considerably smaller MMN for the omissions in the standard (S2–S4, containing ‘silent rests’). And since the omission in the deviant-control (Dcontrol) is expected – the pattern is presented repeatedly –, there as well no MMN is predicted. If these three aspects are observed (as they were found in human adults and newborns [20]), they suggest that a regular beat is extracted from the auditory stimulus.
This could be interpreted as evidence against the vocal learning hypothesis.

Figure 5 shows that the electrical brain responses elicited by omissions in the standard (S2–S4) and deviant-control (Dcontrol) are relatively flat, and different from the deviant (D), with the latter eliciting a more pronounced negative peak, most notably in monkey Y. This suggest a similar result as was found human adults and newborns. However, the ERP response to S1 (dotted black line in Figure 5) is not different from that in response to D (solid red line in Figure 5), while D contains an omission and S1 does not. This seriously weakens the interpretation that the monkeys are able to extract the beat from the stimulus.

Mean amplitudes of responses elicited by standard and deviant stimuli were measured within a time window centered on the absolute maximum of the D minus S2–4 difference waves (see Table 3 and the early gray-shaded windows in Figure 5).

For monkey A an ANOVA with factors Type (S1 vs. S2 vs. S3 vs. S4 vs. Dcontrol vs. D) × Electrode (Fz vs. Cz vs. Pz vs. F3 vs. F4) in the early window (105–153 ms) showed significant main effects in Type (F(5, 37269) = 89.318, P<0.0001, η² = 0.012) and Electrode (F(3,006, 112063.6) = 11.221, P<0.0001, η² <0.001, ζ = 0.752), as well as a significant Electrode × Type (F (15,059, 112063.6) = 7.475, P<0.0001, η² = 0.001, ζ = 0.752) interaction. Tukey unequal-N HSD post-hoc tests were performed. All channels differed from each other (df = 149076, P<0.05) except for Cz, F3 and F4 not differing from each other. All Types differed from each other and S3 from S4. All Electrodes differed from each other and S1 from S2.

For monkey Y an ANOVA with factors Type (S1 vs. S2 vs. S3 vs. S4 vs. Dcontrol vs. D) × Electrode (Fz vs. Cz vs. Pz vs. F3 vs. F4) in the early window (73–123 ms) showed significant main effects in Type (F(5, 49071) = 74.323, P<0.0001, η² = 0.008) and Electrode (F(2,412, 118344.7) = 48.423, P<0.0001, η² = 0.001, ζ = 0.603), as well as a significant Electrode × Type (F (12,059, 118344.7) = 9.479, P<0.0001, η² = 0.001, ζ = 0.603) interaction. Tukey unequal-N HSD post-hoc tests were performed. All channels differed from each other (df = 196284, P<0.05) except for F3 and F4 and Fz not differing from each other. All Types differed from each other (df = 49071, P<0.01), except D, Dcontrol and S1 from each other and S1 from S2.

In the current study we demonstrate for the first time that an MMN-like ERP component can be measured in rhesus monkeys (Macaca mulatta), both for pitch deviants (Experiment 1) and omissions (Experiment 2). Together these results provide support for the idea that ERP and MMN can be used as an index of the detection of regularity-violations as part of a predictive process, rather than just sample matching to sensory memory [28].

In addition, we showed that rhesus monkeys are not able to detect the regularity induced by a varying rhythm, while being sensitive to the rhythmic grouping structure. These findings are in support of the hypothesis that beat induction (the cognitive mechanism that supports the perception of a regular pulse from a varying rhythm) is species-specific, and it is likely restricted to vocal learners such as a selected group of bird species [4], while absent in nonhuman primates such as rhesus monkeys [7]. This is evidence in support of the vocal learning hypothesis.

Furthermore, the results are in line with the auditory timing dissociation hypothesis, suggesting rhythm perception to be distinct from beat perception [10,11,12]. However, the current paradigm, with just a few electrodes measuring EEG, does not allow us to say anything about the brain networks that might be involved. For this fMRI and other brain imaging techniques with a high spatial resolution are needed [29].

And finally, the current study suggests, together with the few existing studies on auditory [16] and visual [30] processing in monkeys, EEG to be a worthwhile, non-invasive alternative in the study of cognitive and neural processing in primates.
Acknowledgments
The research of H.H. and G.H. is part of the Research Priority Area ‘Brain & Cognition’ at the University of Amsterdam. The first author (H.H.) is supported by the Hendrik Muller chair designated on behalf of the Royal Netherlands Academy of Arts and Sciences (KNAW). We thank Raul Paulin for his technical assistance. We are grateful to István Winkler, Fleur Bouwer and two anonymous reviewers for their comments on an earlier version of this manuscript.

Author Contributions
Conceived and designed the experiments: HH HM GH. Performed the experiments: HM LP RB. Analyzed the data: GH HH. Wrote the paper: HH GH HM.

References

Rhesus Monkeys Detect Rhythmic Groups in Music