



**HAL**  
open science

## Rhythmic training improves temporal conversational abilities in children with hearing loss

Céline Hidalgo, Jacques Pesnot-Lerousseau, Patrick Marquis, Stéphane Roman, Daniele Schön

► **To cite this version:**

Céline Hidalgo, Jacques Pesnot-Lerousseau, Patrick Marquis, Stéphane Roman, Daniele Schön. Rhythmic training improves temporal conversational abilities in children with hearing loss. *Journal of Speech, Language, and Hearing Research*, 2019, 62 (9), pp.3234-3247. 10.1044/2019\_JSLHR-S-18-0349 . hal-02344476

**HAL Id: hal-02344476**

**<https://hal.science/hal-02344476>**

Submitted on 4 Nov 2019

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



## Rhythmic training improves temporal conversational abilities in children with hearing loss

Journal:	<i>Journal of Speech, Language, and Hearing Research</i>
Manuscript ID	Draft
Manuscript Type:	Research Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Hidalgo, Céline; Laboratoire Parole et Langage, Sciences du Langage; Institut de Neurosciences des Systèmes, Neurosciences Pesnot--Lerousseau, Jacques; Institut de Neurosciences des Systèmes, Neurosciences Marquis, Patrick; Institut de Neurosciences des Systèmes, Neurosciences Roman, Stéphane; Hopital de la Timone, ORL pédiatrique et Chirurgie Cervico-Faciale; Institut de Neurosciences des Systèmes, Neurosciences Nguyen, Noël; Laboratoire Parole et Langage, Sciences du Langage Schon, Daniele; Institut de Neurosciences des Systèmes, Neurosciences
Keywords:	Cochlear Implants, Intervention, Speech, Neuroimaging, Communication

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4

5 **Rhythmic training improves temporal conversational abilities**  
6 **in children with hearing loss**  
7

8 Céline Hidalgo<sup>1,2</sup>, Jacques Pesnot-Lerousseau<sup>2</sup>, Patrick Marquis<sup>2</sup>, Stéphane Roman<sup>2,3</sup>, Noël  
9 Nguyen<sup>1</sup>, Daniele Schön<sup>2</sup>  
10  
11

12  
13 <sup>1</sup>Aix Marseille Univ, CNRS, LPL, Aix-en Provence, France  
14

15 <sup>2</sup>Aix Marseille Univ, Inserm, INS, Inst Neurosci Syst, Marseille, France  
16

17 <sup>3</sup>Pediatric Otolaryngology department, La Timone Children's Hospital (APHM), Marseille, France  
18  
19

20  
21  
22  
23 Corresponding author: Céline Hidalgo, celine.hidalgo@univ-amu.fr, Laboratoire Parole et  
24 Langage, UMR 7309, CNRS, Aix-Marseille University, 5 Avenue Pasteur, 13100 Aix-en-  
25 Provence, France  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3

4 **Abstract**  
5  
6

7 During conversation, the ability to adapt to the partner's speech is crucial for an optimal  
8 communicative exchange. In this study, we investigate temporal adaptation capacities of  
9 children with normal hearing and children with cochlear implants (CIs) and/or hearing aids  
10 (HAs), during verbal exchange. We also address the question of the efficiency of a rhythmic  
11 training on temporal adaptation during speech interaction in children with hearing loss. We  
12 recorded EEG in children while they named pictures delivered on a screen, in alternation with  
13 a virtual partner. We manipulated the virtual partner's speech rate (*fast* versus *slow*) and the  
14 regularity of alternation (*regular* versus *irregular*). The group of children with normal hearing  
15 was tested once and the group of children with hearing loss twice: once after 30 minutes of  
16 auditory training and once after 30 minutes of rhythmic training. Both groups of children  
17 adjusted their speech rate to that of the virtual partner and were sensitive to the regularity of  
18 alternation with a less accurate performance following irregular turns. Moreover, irregular  
19 turns elicited an MMN-like response in both groups, showing a detection of temporal  
20 deviancy. Notably, the MMN-like amplitude positively correlated with accuracy in the  
21 alternation task. In children with hearing loss, the effect was more pronounced and long-  
22 lasting following rhythmic training compared with auditory training. These results are  
23 discussed in terms of adaptation abilities in speech interaction and suggest the use of rhythmic  
24 training to improve conversational temporal skills of children with hearing loss.  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46

47 **Keywords**  
48

49 Cochlear implant, rehabilitation, speech, EEG, temporal predictions  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

Rhythmic training improves temporal conversational abilities in children with hearing loss

### Introduction

The most natural and common usage of speech is in conversation. Interactions between interlocutors heavily rely on anticipatory processes in order to optimize communicative exchanges and minimize interruptions (Pickering & Garrod, 2013; Levinson & Torreira, 2015). In fact, as it is the case in any joint action implying two or more individuals, a major key of the success of an optimal communicative exchange is the ability for each interlocutor to temporally predict her/his partner's actions (Sebanz & Knoblich, 2009; Kourtis, Sebanz, & Knoblich, 2013). For instance, anticipating the end of the speech turn on the basis of the speech rate allows turn-taking at an optimal pace (Wilson & Wilson, 2005). An anticipation of turn-ends allows avoiding speech overlap of the interlocutors as well as over-long silences that may break the fluency of the exchange. Moreover, it may also allow a better perception of the grouping and prominence of speech that may in turn facilitate speech spectral processing (Cummins & Port, 1998; Port, 2003; Peelle & Davis, 2012).

This ability to readily take turns is possibly facilitated by the fact that interlocutors tend to adopt a common rhythm, based on shared syllable timing (Street, 1984; Himberg, Hirvenkari, Mandel, & Hari, 2015). This phenomenon is considered as taking place automatically and is often referred to as between-speaker rhythmic convergence.

Recent studies have focused on how these anticipatory skills develop during infancy. It has been shown that 5-month-old babies already engage in turn-taking with their mothers, with few overlaps and short turn-taking windows (Hilbrink, Gattis, & Levinson, 2015).

Children with a prelingual hearing loss (HL), whether equipped with cochlear implant or conventional prostheses, are particularly vulnerable in terms of temporal prediction abilities because of the early auditory deprivation. This has a direct impact upon speech perception abilities, especially in acoustically-degraded environmental conditions, as well as on the mastery of certain communication skills. More precisely, children with HL have difficulties in

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 imitating the speech rate of their interlocutor (i.e. temporal convergence) and this goes along  
5  
6 with reduced speech intelligibility (Freeman & Pisoni, 2017). These children are also less  
7  
8 sensitive than normal-hearing children to the temporal regularity of stress distribution in  
9  
10 speech in an interactive verbal task (Hidalgo, Falk, & Schön, 2017). Adolescents with CI both  
11  
12 use different strategies for repairing communication failures and are less sensitive to prosodic  
13  
14 cues relevant to spoken discourse understanding (Holt, Demuth, & Yuen, 2016; Holt, Yuen,  
15  
16 & Demuth, 2017) compared to normal-hearing peers.  
17

18  
19 In a rehabilitation perspective, it seems essential to take into account the alteration of this type  
20  
21 of communication skills in hearing-impaired children in order to improve the quality of their  
22  
23 verbal interactions as well as the development of their social relations (Hoffman, Quittner, &  
24  
25 Cejas, 2014; Manson, Bryant, Gervais, & Kline, 2013; Wong et al., 2017). An intervention  
26  
27 aimed at improving temporal prediction abilities based on rhythm training seems particularly  
28  
29 relevant.  
30

31  
32 Indeed, in a sentence repetition task, presenting a musical rhythm before each sentence  
33  
34 improves hearing-impaired children's accuracy, even more so when the rhythm of the musical  
35  
36 prime matches that of the sentence (Cason, Hidalgo, Isoard, Roman, & Schön,  
37  
38 2015). Moreover, we (Hidalgo et al., 2017) recently showed that following 30 minutes of  
39  
40 rhythmic training (compared to a control condition), children with HL show an enhanced  
41  
42 capacity to accommodate to a temporally predictable flow of turn exchanges in an  
43  
44 interactional setting. These results fit well with the literature showing the beneficial effect of  
45  
46 musical expertise, particularly in the rhythmical domain, on sensitivity to speech rhythm  
47  
48 (Marie, Magne, & Besson, 2011; Moritz, Yampolsky, Papadelis, Thomson, & Wolf, 2013;  
49  
50 Magne, Jordan, & Gordon, 2016), and that of rhythmic stimulation on speech processing  
51  
52 (Cason, Astésano, & Schön, 2015; Cason & Schön, 2012; Chern, Tillmann, Vaughan,  
53  
54 Gordon, & Gordon, 2017), both in normal people and people with a variety of language  
55  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3 disorders (Kotz, Gunter, & Wonneberger, 2005; Przybylski et al., 2013; Cason, Hidalgo, et  
4 al., 2015; Flaugnacco et al., 2015; Bedoin, Brisseau, Molinier, Roch, & Tillmann, 2016;  
5  
6 Schön & Tillmann, 2015).

7  
8  
9  
10 In the light of the above-mentioned studies illustrating the beneficial effect of rhythmic  
11 stimulation on temporal predictions and the processing of auditory information in both adults  
12 and children (for a review, see Haegens & Zion Golumbic, 2017), we conducted a combined  
13  
14 EEG and behavioral study to measure children's temporal adaptation capacities and to  
15  
16 examine the influence of musical rhythmic training on speech perception and production  
17  
18 abilities in children with HL.

19  
20  
21  
22  
23 More precisely, we ran two experiments. In Experiment 1, children with normal hearing (NH)  
24 were asked to perform a picture-naming task in alternation with a virtual partner (adapted  
25 from Hidalgo et al., 2017). The speech rate of the virtual partner could be slow or fast and the  
26  
27 temporal structure of turns could be regular or irregular. We performed acoustic analyses of  
28  
29 speech production to determine to what extent children converged towards the virtual  
30  
31 partner's (VP) speech rate as well as to measure accuracy and consistency of word stress  
32  
33 placement across regular and irregular turns. Event-related potentials were used to assess the  
34  
35 sensitivity to turn regularity.

36  
37  
38  
39  
40 In Experiment 2, children with HL, wearing either cochlear implants (CIs) or hearing aids  
41  
42 (HAs), did the picture-naming task twice: once following 30 minutes of rhythmic musical  
43  
44 training, and once following 30 minutes of auditory training. We hypothesized that the  
45  
46 rhythmic training would improve the ability of children with HL to predict conversational  
47  
48 dynamics which in turn would facilitate speech perception and production.

49  
50  
51 Overall, the aim of this study was twofold. Firstly, we used a turn-taking task to assess in  
52  
53 normal hearing (NH) children the *speech rate convergence* ability as well as the  
54  
55 *accommodation* ability. to adapt to temporal deviancy in the regularity of the turns.

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 Convergence was assessed by estimating changes of the speech rate in the fast compared to  
5  
6 the slow condition. Accommodation was assessed by estimating changes in alternation in the  
7  
8 irregular compared to the regular condition. Secondly, we tested the hypothesis that a single  
9  
10 session of rhythmic training, by improving temporal prediction, may facilitate perception,  
11  
12 convergence and accommodation to the temporal deviancy in a conversational context in  
13  
14 children with HL.  
15  
16  
17  
18

## 19 Experiment 1

### 20 **Material and Method**

#### 21 **Participants**

22  
23  
24  
25 Twenty-two children with normal hearing (NH) (13 girls) were recruited from an *elementary*  
26  
27 *school* in Marseille (France). They were aged from 6 to 10 years (*mean* = 102.6 months, *SD* =  
28  
29 18.5 months) and were all French native speakers without any known visual, speech,  
30  
31 cognitive or hearing disorder. This experiment was approved by the Ethics Committee Sud  
32  
33 Méditerranée I (n°ID RCB: 2015-A01490-49). All parents signed a consent form.  
34  
35

#### 36 **Stimuli**

37  
38 For the alternation naming task, we selected 46 pictures from the French BD2I database  
39  
40 (Cannard, Blaye, Scheuner, & Bonthoux, 2005). These pictures were named correctly by over  
41  
42 90% of a normative sample of 3 to 8-year-old children (mean score = 98.8%, *SD*=1.6%).  
43  
44 46 picture names (disyllabic words) were recorded in a soundproof booth by a male native  
45  
46 French speaker (henceforth, the virtual partner, VP). Four words were also recorded by an 8-  
47  
48 year-old male native French speaker to be used as an example of the alternating procedure at  
49  
50 the beginning of each block.  
51  
52

53 We performed an automatic word segmentation of the VP's recording using SPPAS (Bigi,  
54  
55 2015, 1.8.0 version) and PRAAT (Boersma & Weenink, 2012). All words were then  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 manipulated to obtain a fast (80% of initial word duration) and a slow (120%) version for  
5  
6 each of them, using a wavelet-based method for audio dilation and compression (Pallone et al,  
7  
8 1999). For both the fast and slow versions, p-centers, taken as rhythmic perceptual anchor  
9  
10 points (Morton, Marcus, & Frankish, 1976), were semi-automatically located on the vowel of  
11  
12 the second, stressed syllable, as the 2/3rd of the vowel energy rise (Cummins & Port, 1998).  
13

### 14 Procedure

15  
16 Before the beginning of the picture-naming task, children were familiarized with the pictures  
17  
18 and the experimental procedure to make sure that the words produced for each picture both  
19  
20 were the expected ones and were pronounced in an intelligible manner. Then, children were  
21  
22 equipped with a 21-channel electrode cap (International 10/20 system sites) and were seated  
23  
24 in a Faraday booth in front of a computer screen. They were asked to name the pictures  
25  
26 displayed on the screen, in alternation with a virtual partner (Figure 1).  
27  
28

29 =====

30  
31  
32 PLEASE INSERT FIGURE 1 AROUND HERE  
33

34 =====

35  
36  
37 The experiment consisted of two separate blocks, one with a slow and one with a fast VP  
38  
39 speech rate. Each block started with 4 pairs of pictures that were named by the adult virtual  
40  
41 partner in perfect alternation with the voice of a pre-recorded 8-year-old boy in order to  
42  
43 establish, implicitly, a regular pace of alternation. Next, 132 pictures were presented  
44  
45 successively on the screen and the child was instructed to name the pictures in alternation  
46  
47 with the VP. Care was taken to avoid semantic or phonological priming between successive  
48  
49 words. A given word pair (VP-child) never appeared twice. The child was praised and  
50  
51 encouraged before and between the two blocks. A short pause was given between blocks. The  
52  
53 duration of each block was around 5 minutes.  
54  
55  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss

2  
3 While, as stated above, most utterances of the VP were presented at a regular temporal  
4 interval of 2000ms, ~20% of the words of the VP were anticipated at 1600ms (in both blocks)  
5  
6 and pseudo-randomly distributed across trials.  
7  
8

9  
10 This resulted in a 2 by 2 factorial design manipulating the Regularity of alternation (*regular*  
11 or *irregular*) and Speech Rate (*slow* or *fast*) across blocks. The order of block presentation  
12 (*fast* versus *slow*) was counterbalanced across participants.  
13  
14

15  
16 Stimuli delivery was programmed using the software Presentation (Neurobehavioral Systems  
17 18.0). Pictures were displayed on a computer (DELL Precision T1700, screen resolution 1366  
18 x 768). The voice of the VP was delivered through a 2040 YAMAHA amplifier and two NS  
19 1020 Studio YAMAHA loudspeakers. The output sound volume was adjusted at a  
20 comfortable level for each child. The child's speech was recorded with a lapel microphone  
21 (Sennheiser) linked to a ZOOM H4n numeric recorder at a 44 kHz sampling rate.  
22  
23

24  
25 For every child, we also assessed rhythmic and neuropsychological abilities. Rhythmic  
26 assessment included tapping along a 90 pulses/minute metronome (henceforth paced tapping)  
27 test, tapping in syncopation along a 55 pulses/minute metronome (henceforth syncopated  
28 tapping) and reproduction of 10 rhythms (3 to 8 sounds each) (henceforth rhythmic patterns  
29 reproduction). Children tapped onto a cardboard box containing a ZOOM H4n digital  
30 recorder. Neuropsychological tests were issued from NEPSY and WISC IV. These tests  
31 included digits direct and indirect span test and an auditory attention test requiring to place a  
32 token in a box each time the child heard "red" among other words.  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45

#### 46 **Behavioral data processing and statistical analysis**

47  
48 Children's convergence abilities were evaluated by comparing word duration (in ms) across  
49 the two speech rates (fast and slow).  
50  
51

52  
53 Children's accommodation capacities were determined by the consistency of the children's p-  
54 center placement across trials and the accuracy (temporal asynchrony) relative to the VP's  
55  
56  
57

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 stress placement. First, we extracted the temporal interval (in ms) between the p-centers of the  
5  
6 VP and the p-centers of children (Inter-Word-Interval, IWI). Then we computed circular  
7  
8 statistics (CircStats, Berens, 2009) on the IWI in order to express the children's p-center  
9  
10 placement as a vector in a circular space relative to the expected moment in time (half of the  
11  
12 inter-trial interval of the virtual partner) (statistics also used in Hidalgo et al., 2017 &  
13  
14 Himberg et al., 2015). P-center placement consistency was measured by the vector length, and  
15  
16 accuracy by the vector angle. Words produced with an error, a hesitation or simultaneously  
17  
18 with the virtual partner were excluded from all analyses, resulting in rejection of  
19  
20 approximately 30% of the children's productions.  
21  
22

23 We used R (R Core Team, 2013) and the lme4 package (Bates, Maechler & Bolker,  
24  
25 2013) to fit linear mixed models on single trial data for both word duration and vector angle.  
26  
27 All models were built with participants as random effect. Statistical significance of the fixed  
28  
29 effects was assessed by model comparison on AIC, thus arbitrating between complexity and  
30  
31 explanatory power of the models. Normality and homoscedasticity of the residuals were  
32  
33 systematically visually inspected. Reported p-values are Satterthwaite approximations  
34  
35 obtained with the lmerTest package (Kuznetsova, Brockhoff & Christensen, 2015). As  
36  
37 consistency is always positive and not normally distributed, we applied a logit transform  
38  
39 before model fitting (Falk, Müller & Dalla Bella, 2015). Furthermore, random effects were  
40  
41 dropped for consistency, as this summary statistics (estimated by vector length) gives only  
42  
43 one value per participant and condition.  
44  
45

46 In the *paced* and *syncopated tapping* tasks, tapping times were extracted using Adobe  
47  
48 Audition (2.0) and circular analyses were used to compute the children's consistency and  
49  
50 accuracy.  
51  
52

53 In the *rhythmic patterns reproduction*, the anonymized children's performances were scored  
54  
55 from 1 to 9 (1: no reproduction, 9: perfect performance) by one judge (the last author) with  
56  
57

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3 expertise in music using a blind procedure. The average score across trials was used for  
4  
5 further analyses.  
6

7 Correlations were computed using Spearman's rank, reported with 95% confidence intervals,  
8  
9 between rhythmic measures (paced tapping, and rhythmic patterns reproduction), behavioural  
10  
11 and electrophysiological responses during the turn-taking task.  
12  
13

### 14 **Electrophysiological data processing and statistical analysis**

15 EEG signal processing was done using EEGLAB (Delorme & Makeig, 2004) and custom  
16  
17 Matlab scripts. Continuous data were filtered using a high-pass filter (cutoff frequency 1 Hz)  
18  
19 and major artifacts rejected. Independent Component Analysis (ICA) was used to remove  
20  
21 physiological artifacts such as eye blinks and muscular activity. For the Event-Related  
22  
23 Potentials (ERPs) analysis, data were segmented into 900ms epochs starting 100ms before the  
24  
25 presentation of the VP's words onsets. Further rejection of remaining artifacts was done on  
26  
27 the basis of visual inspection of each epoch and was always lower than 10% of the total  
28  
29 number of epochs in a given condition.  
30  
31

32 We conducted two types of statistical analysis. The first analysis was run on the peak of the  
33  
34 MMN using a classical pairwise comparison. First, a temporal window for peak search was  
35  
36 defined using the average of all trials. Then, for *regular* and *irregular* conditions, the peak  
37  
38 amplitude was computed as the mean value  $\pm 40$ ms around the individual peak. A Region of  
39  
40 Interest (ROI) was defined on the basis of the topography of the average of all conditions,  
41  
42 using a hierarchical clustering technique. The MMN-like ROI comprised 'P3', 'P4', 'O1',  
43  
44 'O2', 'P7', 'P8', and 'Pz' (see Figure 4A). The second analysis consisted of a cluster-based  
45  
46 analysis in the time domain on the same ROI to analyze the differences between *regular* and  
47  
48 *irregular* conditions. Significance was assessed using non-parametric pairwise two-tailed  
49  
50 permutation tests that provide corrected p-values for multiple comparisons. For each  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

Rhythmic training improves temporal conversational abilities in children with hearing loss permutation ( $N = 8,191$ ), time clusters were defined on the basis of temporal adjacency by regrouping samples whose T-statistic was larger than 1.73, *i.e.*  $p\text{-value} \leq 0.05$  for a t-test with 19 degrees of freedom. Cluster-level statistics were then calculated by taking the sum of the T-values within the cluster. Only temporal clusters with corrected  $p\text{-values} \leq 0.05$  are reported.

## Results

*Behavioral results.* The speech rate of the VP affected children's word duration ( $\beta = -33.37$ ,  $SE = 3.76$ ,  $t = -8.85$ ,  $p < .001$ ). More precisely, children's words lasted longer in the *Slow* compared to the *Fast* condition (see Figure 2A).

The analyses of stress placement focused on *consistency*, *i.e.* whether the child placed the stress consistently in the same time window across trials, and *accuracy*, *i.e.* how close the stress was placed with respect to the expected time point.

The regularity of alternation influenced children's consistency and accuracy in stress placement. Children placed word p-centers more consistently in the *Regular* compared to the *Irregular* condition ( $\beta = 0.74$ ,  $SE = 0.28$ ,  $t = 2.667$ ,  $p < .01$ ) (see Figure 2B). They also placed word stresses close to the expected time point in the *Regular* trials while they were late in *Irregular* trials ( $\beta = -0.81$ ,  $SE = 0.03$ ,  $t = -24.09$ ,  $p < .001$ , Figure 2B).

=====

PLEASE INSERT FIGURE 2 AROUND HERE

=====

*Electrophysiological results.* Results showed a MMN-like effect following Irregular trials ( $ES = -3.7\mu V$ ,  $t(1,19) = -5.5834$ ,  $p < 0.001$ ). This effect was significant across a long-lasting time cluster, from 124 to 492ms after stimulus onset ( $p < 0.01$ ). Correlation analysis on the peak amplitude of the MMN-like effect and the vector length showed that children who were more

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 sensitive to the temporal deviancy of the virtual partner, *i.e.* with a large MMN-like effect,  
5  
6 were also more consistent in the turn-taking task, *i.e.* with a high vector length (*Regular*  $r =$   
7  
8  $.58$ , CI  $[.85, .14]$ ; *Irregular*  $r = .44$ , CI  $[.73, .003]$ ). MMN-like amplitude (MMN-like effect  
9  
10 size in the significant cluster) was also positively correlated with the accuracy in stress  
11  
12 placement during the *Irregular* intervals ( $r = .53$ ; CI  $[.09, .85]$ ). Finally, we also found a  
13  
14 positive correlation between children consistency in the tapping task and the turn-taking task  
15  
16 during *Regular* intervals ( $r = .50$  CI  $[.07, .75]$ ). The reproduction of rhythmic patterns did not  
17  
18 show clear correlations with any of the other variables.  
19  
20  
21  
22

## 23 Experiment 2

### 24 **Material and methods**

#### 25 **Participants**

26  
27  
28 Sixteen children with HL (7 girls) wearing bilateral or unilateral cochlear implants (CIs)  
29  
30 and/or Hearing Aids (HAs) (see Table 1 for details) were recruited, mostly via the ENT  
31  
32 paediatric department at the Timone Hospital in Marseilles. All but two were enrolled in a  
33  
34 mainstream primary school. They were aged from 6 to 10 years (*mean* = 102 months, *SD* =  
35  
36 15.6 months) and were all native speakers of French without any reported visual or associated  
37  
38 speech and cognitive impairment. Data of two participants were excluded because of poor  
39  
40 EEG data quality. This experiment was approved by the Ethics Committee Sud Méditerranée  
41  
42 I (n°ID RCB: 2015-A01490-49).  
43  
44  
45

46  
47 =====

48  
49 PLEASE INSERT TABLE 1 AROUND HERE

50  
51 =====  
52  
53  
54  
55  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4  
5

### 6 **Stimuli and procedure**

7  
8 The stimuli, task and procedure were identical to Experiment 1 with the exception that  
9  
10 children with HL performed the task twice: once after 30 minutes of a speech-therapy like  
11  
12 auditory training, and once after 30 minutes of a session of active rhythm. The two sessions  
13  
14 were always separated by at least one week and their order was counterbalanced across  
15  
16 children.  
17

18  
19 The rhythmic training comprised the following exercises: Follow the beat (balance the arms  
20  
21 and walk with a metronome). Structure the beat into meter (listen and tap the strong beat with  
22  
23 the feet and feel and then tap other beats clapping hands with therapist). Learn a new rhythm  
24  
25 (listen to music and find a repetitive rhythm, move to it and tap using claves). Follow metric  
26  
27 changes (listen to music and change body movement type with metrical changes). Body  
28  
29 tapping (in absence of an external stimulus clap hands, tap chest, stop and keep internal beat).  
30  
31 Beat boxing (produce rhythmic patterns with mouth, alone and with therapist).  
32  
33

34  
35 The auditory training comprised the following exercises: Timbre recognition across categories  
36  
37 (recognize sounds belonging to different categories: animals, musical instruments,  
38  
39 environmental sounds). Timbre recognition within categories (recognize sounds belonging to  
40  
41 the same category: animals, musical instruments, environmental sounds). Sound sequences  
42  
43 recognition across categories (recognize sequences of increasing length comprising sounds  
44  
45 belonging to different categories). Sound sequences recognition within categories (recognize  
46  
47 sequences of increasing length comprising sounds belonging to a same category). The level of  
48  
49 difficulty in these exercises was manipulated by reducing the timbral difference between  
50  
51 sounds.  
52  
53

### 54 **Processing and statistical analyses**

55  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss

2  
3 Behavioral analyses were identical to Experiment 1. We tested the effects of speech rate,  
4  
5 regularity and training as well as all the interactions.  
6  
7

8 EEG data processing was also identical to Experiment 1 with the only exception that a second  
9  
10 ICA was run on EEG epoched data to isolate and remove the potential artefacts generated by  
11  
12 the cochlear implant or hearing aids (Campos Viola et al., 2012). Spatial ROI for MMN-like  
13  
14 effect was the same as the NH children. Statistical analyses were also the same, with the only  
15  
16 exception that the threshold for cluster statistic in time was set to 1.77, *i.e.*  $p\text{-value} \leq 0.05$  for  
17  
18 a t-test with 13 degrees of freedom.  
19  
20

21 In order to reduce the number of comparisons we only computed correlations on the  
22  
23 correlated variables found in the NH group analysis, *i.e.* those with  $r > .40$ . Data from the  
24  
25 Rhythmic and the Auditory sessions were averaged.  
26  
27

## 28 **Results**

29  
30  
31 *Behavioral results.* As for NH children, the speech rate of the virtual partner affected the  
32  
33 speech rate of children with HL, in both conditions of stimulation (*auditory Training* and  
34  
35 *rhythmic Training*). More precisely, children's word durations were shorter in the *fast*  
36  
37 condition compared to the *slow* condition after both *Auditory training* ( $\beta = -39.75$ ,  $SE = 3.86$ ,  
38  
39  $t = -10.27$ ,  $p < .001$ ) and *Rhythmic training* ( $\beta = -42.24$ ,  $SE = 3.76$ ,  $t = -11.22$ ,  $p < .001$ ). The  
40  
41 interaction term did not improve the fit of the model ( $\beta = 2.22$ ,  $SE = 5.67$ ,  $t = 3.92$ ,  $p = .695$ )  
42  
43 (see Figure 3A and 3C).  
44  
45

46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
PLEASE INSERT FIGURE 3 AROUND HERE

As for NH children, the regularity of alternation influenced stress placement consistency and  
accuracy of children with HL. Children with HL placed the stress more consistently in the

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 *regular* compared to the *irregular* trials ( $F(2.53) = 5.75, p = .005$ ) (Figure 3B and 3D).  
5  
6 They also placed word stresses closer to the expected time point in the *regular* trials compared  
7  
8 to *irregular* trials ( $\beta = -0.66, SE = 0.03, t = -10.27, p < .001$ ) (Figure 3B and 3D). While the  
9  
10 interaction between speech rate and regularity did not improve the model significantly ( $p =$   
11  
12  $0.5$ ), the interaction between training type and regularity of alternation significantly improved  
13  
14 the fit of the model for accuracy data: the perturbation induced by irregular trials on accuracy  
15  
16 of stress placement was reduced following *Rhythmic training* ( $\beta = -0.66, SE = 0.03, t = -17.61,$   
17  
18  $p < .001$ ) compared to *Auditory training* ( $\beta = -0.79, SE = 0.03, t = -21.39, p < .001$  see Figure  
19  
20 3B).  
21  
22

23 *Electrophysiological results.* Analyses on the peak showed a MMN-like effect following both  
24  
25 *Rhythmic Training* and *Auditory Training* ( $t(1, 47) = -6.4654, p < .0001$ ). The MMN peak  
26  
27 amplitude effect did not differ across the two conditions of stimulation ( $t(1, 13) = 1.1778, p =$   
28  
29  $0.26$ ).  
30

31 By contrast, clusters analysis revealed a long lasting MMN-like effect from 239 to 469ms  
32  
33 following *Rhythmic Training* ( $p < .05$ ) (see figure 4B) while no cluster reached significance  
34  
35 following *Auditory Training* ( $p > 0.4$ ) (see Figure 4C).  
36  
37

38 Correlation analyses revealed that children who were more sensitive to the temporal deviancy  
39  
40 of the virtual partner (MMN-like effect size in the significant cluster) were also more accurate  
41  
42 in the stress placement in the *irregular* turns ( $r = .42$  CI  $[-.03, .65]$ ).  
43  
44

45 =====

46  
47  
48 PLEASE INSERT FIGURE 4 AROUND HERE  
49

50 =====

## 51 52 53 Discussion 54 55 56 57 58 59 60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss

2  
3  
4 The aim of this study was twofold. Firstly, we measured the speech rate convergence and  
5  
6 temporal accommodation abilities in 6 to 10-year-old children during a turn-taking task with a  
7  
8 virtual partner, and to bridge these abilities to the sensitivity to temporal deviancy as  
9  
10 measured by an MMN-like effect. Secondly, we assessed whether a single 30-minute session  
11  
12 of rhythmic training can enhance temporal prediction in children with hearing loss and, in  
13  
14 turn, affect speech temporal skills that are relevant for a fluent conversation.  
15  
16

17  
18 Results show that both children with NH and children with HL converge towards the speech  
19  
20 rate of a virtual partner. Moreover, in both children groups, stress placement is more  
21  
22 consistent and accurate following regular VP turns compared to irregular turns. Most  
23  
24 importantly, the rhythmic training session improves the accuracy of children with HL in  
25  
26 placing the stress at irregular turns. In other words, rhythmic training seems to endow children  
27  
28 with greater flexibility in adapting to a sudden change in the temporal context. Finally, both  
29  
30 groups (NH-HL) show an MMN-like response to irregular turns of the virtual partner. This  
31  
32 response is larger in children with HL following rhythmic training compared to the same  
33  
34 children following auditory training. We will first discuss children convergence abilities by  
35  
36 analysing the effects of the virtual partner's speech rate on children speech, then the effect of  
37  
38 alternation regularity on children's temporal accommodation abilities and, in a second step,  
39  
40 we will discuss the effects of rhythmic training on temporal accommodation capacities of  
41  
42 children with HL.  
43  
44  
45

### 46 **Speech rate convergence with a virtual partner**

47  
48  
49 One innovative aspect of this experimental design is that it allows, by manipulating the virtual  
50  
51 partner's speech rate, to estimate the speech rate convergence, namely the natural tendency to  
52  
53 minimize the speech rate difference between partners in a conversation (Manson et al., 2013;  
54  
55 Schultz, O'Brien, Phillips, & Mcfarland, 2016). Our results confirm previous evidence of this  
56  
57

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 phenomenon in a real communication setup (R. L. Street, Street, & Van Kleeck, 1983; R. L.  
5  
6 Street & Cappella, 1989) extending it to an interaction with a virtual non-adaptive partner and  
7  
8 with single words. Importantly, we demonstrate speech rate convergence in a population of  
9  
10 children with HL. While Freeman & Pisoni, (2017) found a less consistent convergence in  
11  
12 cochlear implant users compared to normal hearing children, this could be due to important  
13  
14 differences in the setup, which include using a natural and thus variable interlocutor (Freeman  
15  
16 & Pisoni) versus a constant speech rate in the present study, and the use of a sentence  
17  
18 repetition task versus a much easier object naming task. Thus, our experimental design, using  
19  
20 an alternating naming task, seems particularly suitable to assess convergence abilities even in  
21  
22 populations wherein these abilities may be impaired.  
23  
24  
25

### 26 **Temporal accommodation abilities and speech-turn regularity**

27  
28  
29 The consistency of accent placement in regular turns for the two groups (NH-HL)  
30  
31 corroborates our previous results (Hidalgo et al., 2017). In that study, children had to name  
32  
33 words whose accent patterns (number of syllables) could be identical or not to those of the  
34  
35 virtual partner with which the children interacted; the turns of speech were thus more or less  
36  
37 regular. Overall, children were consistent in placing word accents, especially when the words  
38  
39 they had to produce had the same accent pattern as the words produced by the virtual partner.  
40  
41  
42

43 In the present study, children in both groups (NH and HL) were more accurate during regular  
44  
45 than irregular turns in placing the stress of the word at the « expected » moment, that is  
46  
47 precisely in between two turns of the virtual partner. Interestingly, during regular turns,  
48  
49 children tended to place the stress slightly before this expected moment. This is reminiscent of  
50  
51 the negative asynchrony described in sensori-motor tapping tasks and has been interpreted in  
52  
53 terms of anticipatory behaviour (Repp, 2005) that can be absent in other species (Zarco,  
54  
55 Merchant, Prado, & Mendez, 2009; Patel, 2014; Merchant & Honing, 2014). By contrast,  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3 during irregular turns, children were late in placing the word stress. During these (irregular)  
4 turns, the distance between the consecutive accents of the PV was suddenly shortened, which  
5 implied for the child a local readjustment of the internal temporal model of the alternation.  
6  
7 According to the Adaptation and Anticipation Model (ADAM) model (van der Steen &  
8 Keller, 2013), interacting individuals generate temporal predictions on both their own and  
9 their partner's actions. This relies on an anticipation mechanism based on the temporal  
10 regularities of the partner's behavior and an adaptation mechanism allowing to adjust to local  
11 temporal (phase) variations. During the irregular turns, children need both the anticipation  
12 module to estimate the duration of the next interval and the adaptation module to make local  
13 corrections to adjust to the temporal deviation of the VP.  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25

26 ERP results indicate that the auditory system of normal-hearing children was sensitive to the  
27 deviation from temporal expectations in speech turns, similarly to temporal deviations in  
28 rhythmic musical sequences (Vuust et al., 2005). Interestingly, because the VP was following  
29 a very slow pace (2000ms between words), temporal expectation possibly emerged from the  
30 subdivision of this slow regular pace by the child turns (~1000ms). This is supported by the  
31 correlation between the temporal accommodation capacities of the child and the amplitude of  
32 the MMN-like effect. Interestingly, the MMN-like measure was issued from a temporal  
33 cluster lasting up to ~500ms which may imply a role of attentive and conscious processing. In  
34 other words, the better the child consciously perceives a change in the regularity of the  
35 alternation, the better s/he can predict and adapt speech turns. This correlation of performance  
36 of normal hearing children and children with hearing loss between perception and production  
37 abilities suggests that anticipation and adaptation capacities during verbal interaction are  
38 tightly related to the sensitivity of the auditory system in processing the temporal structure of  
39 speech. The importance for speech accommodation of directing attention and adapting to  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3 temporal deviations is particularly emphasized in deaf children after the rhythmic stimulation  
4  
5 session.  
6  
7  
8  
9  
10  
11  
12  
13

### 14 **Effect of the rhythmic training session on speech perception and temporal** 15 **accommodation abilities in children with HL** 16

17  
18  
19 Children did not show a greater convergence on virtual partner speech rate after the rhythmic  
20 compared to the auditory training possibly because our design, with an artificial partner who  
21 keeps the same speech rate along the blocks, renders the speech rate very easy to reproduce.  
22  
23  
24

25  
26  
27 However, following only 30 minutes of rhythmic training, children with HL improved their  
28 performance in the turn-taking task. More precisely, they became more accurate in temporally  
29 placing the stress of the word following an irregular turn, wherein the virtual partner  
30 anticipates the turn. This is the condition that requires the greatest flexibility to quickly adapt  
31 to the anticipated turn. This result, coupled to the greater and longer-lasting effect on the  
32 ERPs to deviant turns, suggests that the rhythmic training has engendered a more robust and  
33 prompt processing of temporal deviations.  
34  
35  
36  
37  
38  
39  
40  
41  
42

43 This is in line with previous findings showing that musicians are more consistent and accurate  
44 than non-musicians in several types of temporal tasks, and are also more sensitive to temporal  
45 deviations occurring in a regular auditory sequence (Drake, 1993; Rammsayer & Altenmüller,  
46 2006; Repp, 2010; Yee, Holleran, & Riessjones, 1994; Jones & Yee, 1997). Moreover,  
47 musical expertise improves temporal processing not only in music but also in speech at  
48 different temporal scales (Cameron & Grahn, 2014; Geiser, Sandmann, Jäncke, & Meyer,  
49 2010; Marie et al., 2011; Chobert J, Marie C, François C, Schön D, 2011; Elmer, Meyer, &  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 Jäncke, 2012; Sares, Foster, Allen, & Hyde, 2018). When we turn to populations with hearing  
5  
6 loss, cochlear implant users undergoing musical training show a greater sensitivity to fine  
7  
8 temporal modification of sounds, as reflected in larger ERP responses compared to cochlear  
9  
10 implant users without musical training (Timm et al., 2012). Moreover, children with cochlear  
11  
12 implant that practice regular singing show enhanced P3a-like responses to several sound  
13  
14 feature modifications compared to children with cochlear implant that do not practice regular  
15  
16 singing (Torppa, Huotilainen, Leminen, Lipsanen, & Tervaniemi, 2014). Similarly, in the  
17  
18 present study, music training mostly affected the amplitude of the MMN-like component,  
19  
20 which has been described as involved in attentional processes (Gray, Ambady, Lowenthal, &  
21  
22 Deldin, 2004). Thus, it seems that the rhythmic session has enhanced the children's ability to  
23  
24 make accurate temporal predictions on the occurrence of regular turns. Then, small deviations  
25  
26 from regularity may not only be automatically detected by the auditory system, but also  
27  
28 actively processed to adapt speech behavior. This effect is not visible for the same children  
29  
30 following 30 minutes of auditory training. This enhanced prediction is possibly mediated by a  
31  
32 greater involvement of the motor and premotor cortex in musicians (Krause, Schnitzler, &  
33  
34 Pollok, 2010) that in turn affects auditory perception (Merchant, Grahn, Trainor, Rohrmeier,  
35  
36 & Fitch, 2015). In other words, the greater implication of the motor system in auditory  
37  
38 perception improves the precision of temporal prediction of auditory events (Morillon,  
39  
40 Schroeder, & Wyart, 2014; Morillon & Baillet, 2017). Thus, active rhythmic training,  
41  
42 involving body movement and sensorimotor synchronization, has possibly increased the  
43  
44 involvement of motor system in temporal prediction, facilitating the detection of irregular  
45  
46 turns and temporal accommodation. Moreover, the active rhythmic training proposed here  
47  
48 stimulated not only the synchronization abilities on an external rhythm but also the  
49  
50 interpersonal coordination (for instance via rhythm repetition and rhythm exchanges). This  
51  
52 has possibly facilitated the realization of the picture naming alternation task as a joint action  
53  
54  
55  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 to be realized in coordination with the partner. Interestingly, joint action planning compared  
5  
6 with individual action planning can result in amplitude modulations of the P300 (Kourtis et  
7  
8 al., 2013).

9  
10  
11 To conclude, while the regularity in speech turns in our paradigm was exaggerated compared  
12  
13 to natural conversation, one can imagine that the same mechanism is at work in both natural  
14  
15 and controlled exchanges. Thus, rhythmic training could be a powerful tool to facilitate  
16  
17 temporally accurate speech interaction, which in turn will improve speech coordination in  
18  
19 conversation (Konvalinka, Vuust, Roepstorff, & Frith, 2010), and boost engagement in  
20  
21 prosocial and cooperative attitudes (Cirelli, Wan, & Trainor, 2014; Valdesolo, Ouyang, &  
22  
23 DeSteno, 2010).

### 24 25 26 27 **Acknowledgments**

28  
29  
30 Research supported by grants of the Fondation Agir pour l'Audition (APA RD-2016-9),  
31  
32 ANR-16-CE28-0012 RALP, ANR-16-CONV-0002 (ILCB), ANR-11-LABX-0036 (BLRI)  
33  
34 and the Excellence Initiative of Aix-Marseille University (A\*MIDEX). We wish to thank  
35  
36 Romane Pradels and Laura Leone for their contribution in speech data analysis.  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

## Rhythmic training improves temporal conversational abilities in children with hearing loss

Table 1

Child	Age in months (years)	Duration of use of the device (in months)	Age at switch-on or HA wearing (in months)	Type of device	Current hearing Loss without HA(s) or CI(s)	Thresholds at 250-500-1000-2000 Hz	Onset of deafness
1	115 (9.7)	HA:51	64	HA	severe	10-25-35-25	unknown
2	94 (7.10)	CI :70	12 (HA) 24	CI	profound	30-30-30-30	congenital
3	92 (7.8)	CI:40 HA:47	52 18	CI + HA	profound	30-30-35-40	congenital
4	76 (6.6)	CI n°1:64 CI n°2: 64	12 12	+ CI	cophosis	35-25-25-25 35-25-25-25	perilingual
5	116 (9.8)	CI:80	30	CI	profound	30-25-25-20	congenital
6	82 (6.10)	HA:72	6	HA + HA	severe	20-20-25-35 25-30-30-35	congenital
7	85 (7.1)	HA:77	8	HA +	moderate	10-10-15-30 15-20 15-30	congenital

## Rhythmic training improves temporal conversational abilities in children with hearing loss

			HA					
8	96 (8.8)	CI:66	16 (HA)	CI	profound	25-25-25-25		congenital
			30					
9	111(9.3)	CI n°1:104	7	CI		30-25-25-20		
		CI n°2:94	17	+	profound	30-30-35-35		unknown
				CI				
10	88 (7.4)	CI n°1:74	14	CI		25-35-40-35		
		CI n°2:65	23	+	profound	20-30-40-35		congenital
				CI				
11	123 (10.3)	HA:87	36	HA	severe	10-20-20-25		congenital
						15-20-25-25		
12	111 (9.3)	CI:93	18	CI	profound	35-25-40-30		congenital
				CI				
13	126 (10.6)	CI n°1:60	66	+	profound	15-20-20-35		
		CI n°2:23	103	CI		15-20-20-20		progressive
				CI				
14	93 (7.9)	CI n°1:60	23	+	profound	25-35-40-35		
		CI n°2:58	35	CI		20-30-40-35		congenital

**Table 1. Demographic data of children with HL.** HA: hearing aid; CI: cochlear implant (in case of bilateral implantation, n°1 means the duration of use of the 1st implant and n°2 the duration of use of the second contralateral implant, HA in parenthesis means the onset of

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 wearing a hearing device before implantation). Thresholds are given for each device (children  
5  
6 wearing a cochlear implant without contralateral hearing aid like Child n°2, did not have any  
7  
8 usable acoustic hearing in the unaided ear).  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

For Peer Review

1 Rhythmic training improves temporal conversational abilities in children with hearing loss

2  
3  
4 Figures Legends

5  
6  
7 **Figure 1. Task and procedure.** A. Schematic representation of the task. The virtual partner  
8 pronounces isolated words at *regular* (blue, 2000 ms) or *irregular* (red, 1600 ms) intervals.  
9 The child names the objects presented on the screen in alternation with the virtual partner.  
10 The speech rate of the virtual partner can be *fast* (light blue, top panel) or *slow* (dark blue,  
11 bottom panel). The vertical arrows indicate the p-center placement of the words. IWI stands  
12 for Inter Words Intervals, namely the distance between the virtual partner p-center and the  
13 child p-center. WD stands for Words Duration, namely the duration of the words pronounced  
14 by the child. B. Schematic representation of the procedure. Normal hearing (NH) children ran  
15 the task once and children with hearing loss (HI) ran the task twice (order was  
16 counterbalanced). For all figures, the ear represents children with normal hearing, the maracas  
17 represent children with hearing loss after rhythmic training, and the loudspeaker represents  
18 children with hearing loss after auditory training.  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34

35  
36 **Figure 2. Behavioral results for NH children.** A. Convergence results. Effect of the virtual  
37 partner's speech rate on mean word duration in the fast and slow conditions. B.  
38 Accommodation results. Effect of the regularity of alternation on children's stress placement.  
39 Left panel depicts the consistency of stress placement, represented by the vector length (from  
40 0 to 1). Higher values represent better performances. Right panel depicts the accuracy of  
41 stress placement. Time zero represents a stress placement at the expected time. Positive values  
42 represent late responses, and negative values represent early responses.  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52

53  
54 **Figure 3. Behavioral results for HI children.** A. Convergence results following a 30-min  
55 rhythmic training. Effect of the virtual partner speech rate on mean word duration in the fast  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 and slow conditions. B. Accommodation results following a 30-min rhythmic training. Effect  
5  
6 of the regularity of alternation on children stress placement. Left panel depicts the consistency  
7  
8 of stress placement, represented by the vector length (from 0 to 1). Higher values represent  
9  
10 better performances. Right panel depicts the accuracy of stress placement. Time zero  
11  
12 represents a stress placement at the expected time. Positive values represent late responses,  
13  
14 and negative values represent early responses. C-D. Convergence and accommodation results  
15  
16 following a 30-min auditory training.  
17  
18  
19  
20

21 **Figure 4. Electrophysiological (EEG) results.** Grand average of Event Related Potentials for  
22  
23 regular and irregular trials. Time zero is the onset of the word pronounced by the virtual  
24  
25 partner. Shadowed areas represent significant time clusters ( $p < .05$ ). A. NH children. B. HI  
26  
27 children after rhythmic training. C. HI children after auditory training.  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3

#### 4 **References**

5  
6 Bates, D., & Maechler, M. (2009). *Dai B lme4: Linear mixed-effects models using S4 classes.*

7  
8 R package version 0.999375-28.  
9

10  
11 Bedoin, N., Brisseau, L., Molinier, P., Roch, D., & Tillmann, B. (2016). Temporally Regular

12  
13 Musical Primes Facilitate Subsequent Syntax Processing in Children with Specific

14  
15 Language Impairment. *Frontiers in Neuroscience, 10*, 245.

16  
17 <https://doi.org/10.3389/fnins.2016.00245>  
18  
19

20  
21 Berens, P. (2009). CircStat: A MATLAB toolbox for circular statistics. *Journal of Statistical*

22  
23 *Software, 31*(10), 1–21. <https://doi.org/10.1002/wics.10>  
24  
25

26  
27 Bigi, B. (2015). SPPAS-multi-lingual approaches to the automatic annotation of speech. *The*

28  
29 *Phonetician-International Society of Phonetic Sciences, (111-112)*, 54-69.  
30

31  
32 Cameron, D. J., & Grahn, J. A. (2014). Enhanced timing abilities in percussionists generalize

33  
34 to rhythms without a musical beat. *Frontiers in Human Neuroscience, 8*(December),

35  
36 1003. <https://doi.org/10.3389/fnhum.2014.01003>  
37  
38

39  
40 Cannard, C., Blaye, A., Scheuner, N., & Bonthoux, F. (2005). Picture naming in 3- to 8-year-

41  
42 old French children: methodological considerations for name agreement. *Behavior*

43  
44 *Research Methods, 37*(3), 417–425. <https://doi.org/10.3758/BF03192710>  
45

46  
47 Cason, N., Astésano, C., & Schön, D. (2015). Bridging music and speech rhythm: rhythmic

48  
49 priming and audio-motor training affect speech perception. *Acta Psychologica, 155*, 43–

50  
51 50. <https://doi.org/10.1016/j.actpsy.2014.12.002>  
52

53  
54 Cason, N., Hidalgo, C., Isoard, F., Roman, S., & Schön, D. (2015). Rhythmic priming

55  
56 enhances speech production abilities: Evidence from prelingually deaf children.  
57  
58  
59  
60

- 1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 *Neuropsychology*, 29(1), 102–107. <https://doi.org/10.1037/neu0000115>  
5  
6  
7 Cason, N., & Schön, D. (2012). Rhythmic priming enhances the phonological processing of  
8  
9 speech. *Neuropsychologia*, 50(11), 2652–8.  
10  
11 <https://doi.org/10.1016/j.neuropsychologia.2012.07.018>  
12  
13  
14 Chern, A., Tillmann, B., Vaughan, C., Gordon, R. L., & Gordon, R. (2017). New evidence of  
15  
16 a rhythmic priming effect that enhances grammaticality judgments in children.  
17  
18 <https://doi.org/10.1101/193961>  
19  
20  
21 Chobert J, Marie C, François C, Schön D, B. M. (2011). Enhanced passive and active  
22  
23 processing of syllables in musician children. *J Cogn Neurosc.*, 23(12), 3874–3887.  
24  
25 [https://doi.org/10.1162/jocn\\_a\\_00088](https://doi.org/10.1162/jocn_a_00088)  
26  
27  
28 Cirelli, L. K., Wan, S. J., & Trainor, L. J. (2014). Fourteen-month-old infants use  
29  
30 interpersonal synchrony as a cue to direct helpfulness. *Philosophical Transactions of the*  
31  
32 *Royal Society B: Biological Sciences*, 369(1658), 20130400–20130400.  
33  
34 <https://doi.org/10.1098/rstb.2013.0400>  
35  
36  
37 Cummins, F., & Port, R. (1998). Rhythmic constraints on stress timing in English. *Journal of*  
38  
39 *Phonetics*, 26(2), 145–171. <https://doi.org/10.1006/jpho.1998.0070>  
40  
41  
42  
43 Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-  
44  
45 trial EEG dynamics including independent component analysis. *Journal of Neuroscience*  
46  
47 *Methods*, 134, 9–21. Retrieved from  
48  
49 <https://cloudfront.escholarship.org/dist/prd/content/qt52k1t4sz/qt52k1t4sz.pdf>  
50  
51  
52 Drake, C. (1993). Reproduction of musical rhythms by children, adult musicians, and adult  
53  
54 nonmusicians. *Perception & Psychophysics*, 53(1), 25–33.  
55  
56  
57  
58  
59  
60

- 1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 <https://doi.org/10.3758/BF03211712>  
5
- 6 Elmer, S., Meyer, M., & Jäncke, L. (2012). The spatiotemporal characteristics of elementary  
7  
8 audiovisual speech and music processing in musically untrained subjects. *International*  
9  
10 *Journal of Psychophysiology*, *83*(3), 259–268.  
11  
12 <https://doi.org/10.1016/j.ijpsycho.2011.09.011>  
13  
14  
15
- 16 Falk, S., Müller, T., & Dalla Bella, S. (2015). Non-verbal sensorimotor timing deficits in  
17  
18 children and adolescents who stutter. *Frontiers in Psychology*, *6*, 847.  
19  
20 <https://doi.org/10.3389/fpsyg.2015.00847>  
21  
22
- 23 Flaugnacco, E., Lopez, L., Terribili, C., Montico, M., Zoia, S., & Schön, D. (2015). Music  
24  
25 Training Increases Phonological Awareness and Reading Skills in Developmental  
26  
27 Dyslexia: A Randomized Control Trial. *Plos One*, *10*(9), e0138715.  
28  
29 <https://doi.org/10.1371/journal.pone.0138715>  
30  
31  
32
- 33 Freeman, V., & Pisoni, D. B. (2017). Speech rate, rate-matching, and intelligibility in early-  
34  
35 implanted cochlear implant users. *The Journal of the Acoustical Society of America*,  
36  
37 *142*(2), 1043–1054. <https://doi.org/10.1121/1.4998590>  
38  
39
- 40 Geiser, E., Sandmann, P., Jäncke, L., & Meyer, M. (2010). Refinement of metre perception -  
41  
42 training increases hierarchical metre processing. *European Journal of Neuroscience*,  
43  
44 *32*(11), 1979–1985. <https://doi.org/10.1111/j.1460-9568.2010.07462.x>  
45  
46
- 47 Gray, H. M., Ambady, N., Lowenthal, W. T., & Deldin, P. (2004). P300 as an index of  
48  
49 attention to self-relevant stimuli. *Journal of Experimental Social Psychology*, *40*(2),  
50  
51 216–224. [https://doi.org/10.1016/S0022-1031\(03\)00092-1](https://doi.org/10.1016/S0022-1031(03)00092-1)  
52  
53
- 54 Haegens, S., & Zion Golumbic, E. (2018). Rhythmic facilitation of sensory processing: A  
55  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss

2  
3 critical review. *Neuroscience & Biobehavioral Reviews*, 86(December), 150–165.

4  
5  
6 <https://doi.org/10.1016/j.neubiorev.2017.12.002>

7  
8 Hidalgo, C., Falk, S., & Schön, D. (2017). Speak on time! Effects of a musical rhythmic

9  
10 training on children with hearing loss. *Hearing Research*, 351(May), 11–18.

11  
12  
13 <https://doi.org/10.1016/j.heares.2017.05.006>

14  
15 Hilbrink, E. E., Gattis, M., & Levinson, S. C. (2015). Early developmental changes in the

16  
17 timing of turn-taking: a longitudinal study of mother–infant interaction. *Frontiers in*

18  
19  
20 *Psychology*, 6(September), 1–12. <https://doi.org/10.3389/fpsyg.2015.01492>

21  
22  
23 Himberg, T., Hirvenkari, L., Mandel, A., & Hari, R. (2015). Word-by-word entrainment of

24  
25 speech rhythm during joint story building. *Frontiers in Psychology*, 6(June), 1–6.

26  
27  
28 <https://doi.org/10.3389/fpsyg.2015.00797>

29  
30 Hoffman, M. F., Quittner, a. L., & Cejas, I. (2014). Comparisons of Social Competence in

31  
32 Young Children With and Without Hearing Loss: A Dynamic Systems Framework.

33  
34  
35 *Journal of Deaf Studies and Deaf Education*, 20(2), 115–124.

36  
37  
38 <https://doi.org/10.1093/deafed/enu040>

39  
40 Holt, C. M., Demuth, K., & Yuen, I. (2016). The Use of Prosodic Cues in Sentence

41  
42 Processing by Prelingually Deaf Users of Cochlear Implants. *Ear and Hearing*, 37(4),

43  
44  
45 e256–e262. <https://doi.org/10.1097/AUD.0000000000000253>

46  
47 Holt, C. M., Yuen, I., & Demuth, K. (2017). Discourse Strategies and the Production of

48  
49 Prosody by Prelingually Deaf Adolescent Cochlear Implant Users, 101–108.

50  
51  
52 Jones, M. R., & Yee, W. (1997). Sensitivity to time change: The role of context and skill.

53  
54  
55 *Journal of Experimental Psychology: Human Perception and Performance*, 23(3), 693–

- 1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 709. <https://doi.org/10.1037/0096-1523.23.3.693>  
5  
6 Klein, C., Liem, F., Hänggi, J., Elmer, S., & Jäncke, L. (2015). The “silent” imprint of  
7  
8 musical training. *Human Brain Mapping, 00*(August), n/a-n/a.  
9  
10 <https://doi.org/10.1002/hbm.23045>  
11  
12  
13 Konvalinka, I., Vuust, P., Roepstorff, A., & Frith, C. D. (2010). Follow you, follow me:  
14  
15 Continuous mutual prediction and adaptation in joint tapping. *The Quarterly Journal of*  
16  
17 *Experimental Psychology, 63*(11), 2220–2230.  
18  
19 <https://doi.org/10.1080/17470218.2010.497843>  
20  
21  
22  
23 Kotz, S. A., Gunter, T. C., & Wonneberger, S. (2005). The basal ganglia are receptive to  
24  
25 rhythmic compensation during auditory syntactic processing: ERP patient data.  
26  
27 <https://doi.org/10.1016/j.bandl.2005.07.039>  
28  
29  
30  
31 Kourtis, D., Sebanz, N., & Knoblich, G. (2013). Predictive representation of other people’s  
32  
33 actions in joint action planning: An EEG study. *Social Neuroscience, 8*(1), 31–42.  
34  
35 <https://doi.org/10.1080/17470919.2012.694823>  
36  
37  
38 Krause, V., Schnitzler, A., & Pollok, B. (2010). Functional network interactions during  
39  
40 sensorimotor synchronization in musicians and non-musicians. *NeuroImage, 52*, 245–  
41  
42 251. <https://doi.org/10.1016/j.neuroimage.2010.03.081>  
43  
44  
45 Kuznetsova, A., Brockhoff, P. B., and Christensen, R. H. B. (2014). lmerTest: tests in linear  
46  
47 mixed effects models. R package version 2.0–20. Available at [http://CRAN.R-](http://CRAN.R-project.org/package=lmerTest)  
48  
49 [project.org/package=lmerTest](http://CRAN.R-project.org/package=lmerTest)  
50  
51  
52 Levinson, S. C., & Torreira, F. (2015). Timing in turn-taking and its implications for  
53  
54 processing models of language. *Frontiers in Psychology, 6*(JUN), 1–17.  
55  
56  
57  
58  
59  
60

- 1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 <https://doi.org/10.3389/fpsyg.2015.00731>  
5
- 6 Magne, C., Jordan, D. K., & Gordon, R. L. (2016). Speech rhythm sensitivity and musical  
7  
8 aptitude: ERPs and individual differences. *Brain and Language*.  
9  
10 <https://doi.org/10.1016/j.bandl.2016.01.001>  
11  
12
- 13 Manson, J. H., Bryant, G. a., Gervais, M. M., & Kline, M. a. (2013). Convergence of speech  
14  
15 rate in conversation predicts cooperation. *Evolution and Human Behavior*, 34, 419–426.  
16  
17 <https://doi.org/10.1016/j.evolhumbehav.2013.08.001>  
18  
19
- 20 Marie, C., Magne, C., & Besson, M. (2011). Musicians and the metric structure of words.  
21  
22 *Journal of Cognitive Neuroscience*, 23(2), 294–305.  
23  
24 <https://doi.org/10.1162/jocn.2010.21413>  
25  
26
- 27 Merchant, H., Grahn, J., Trainor, L., Rohrmeier, M., & Fitch, W. T. (2015). Finding the beat:  
28  
29 a neural perspective across humans and non-human primates. *Philosophical*  
30  
31 *Transactions of the Royal Society of London. Series B, Biological Sciences*, 370,  
32  
33 20140093. <https://doi.org/10.1098/rstb.2014.0093>  
34  
35  
36
- 37 Merchant, H., & Honing, H. (2014). Are non-human primates capable of rhythmic  
38  
39 entrainment? Evidence for the gradual audiomotor evolution hypothesis. *Frontiers in*  
40  
41 *Neuroscience*, 7(8 JAN), 1–8. <https://doi.org/10.3389/fnins.2014.00274>  
42  
43  
44
- 45 Morillon, B., & Baillet, S. (2017). Motor origin of temporal predictions in auditory attention.  
46  
47 *Proceedings of the National Academy of Sciences of the United States of America*,  
48  
49 114(42), E8913–E8921. <https://doi.org/10.1073/pnas.1705373114>  
50  
51
- 52 Morillon, B., Schroeder, C. E., & Wyart, V. (2014). Motor contributions to the temporal  
53  
54 precision of auditory attention. *Nature Communications*, 5, 5255.  
55  
56  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss

2  
3  
4 <https://doi.org/10.1038/ncomms6255>

5  
6 Moritz, C., Yampolsky, S., Papadelis, G., Thomson, J., & Wolf, M. (2013). Links between  
7  
8 early rhythm skills, musical training, and phonological awareness. *Reading and Writing*,  
9  
10 26(5), 739–769. <https://doi.org/10.1007/s11145-012-9389-0>

11  
12  
13  
14 Morton, J., Marcus, S. M., & Frankish, C. R. (1976). Perceptual Centers (P-centers).  
15  
16 *Psychological Review*, 83(5), 405–408. <https://doi.org/10.1037/0033-295X.83.5.405>

17  
18  
19 Pallone, G., Boussard, P., Daudet, L., Guillemain, P., & Kronland-Martinet, R. (1999,  
20  
21 December). A wavelet based method for audio-video synchronization in broadcasting  
22  
23 applications. In *Proceedings of the International Conference on Digital Audio Effects*,  
24  
25 Norway.

26  
27  
28 Patel, A. D. (2014). The Evolutionary Biology of Musical Rhythm: Was Darwin Wrong?  
29  
30 *PLoS Biology*, 12(3). <https://doi.org/10.1371/journal.pbio.1001821>

31  
32  
33 Peelle, J. E., & Davis, M. H. (2012). Neural Oscillations Carry Speech Rhythm through to  
34  
35 Comprehension. *Frontiers in Psychology*, 3(September), 320.  
36  
37 <https://doi.org/10.3389/fpsyg.2012.00320>

38  
39  
40 Petersen, B., Weed, E., Sandmann, P., Brattico, E., Hansen, M., Sørensen, S. D., & Vuust, P.  
41  
42 (2015). Brain Responses to Musical Feature Changes in Adolescent Cochlear Implant  
43  
44 Users. *Frontiers in Human Neuroscience*, 9, 7.  
45  
46 <https://doi.org/10.3389/fnhum.2015.00007>

47  
48  
49 Pickering, M. J., & Garrod, S. (2013). An integrated theory of language production and  
50  
51 comprehension. *The Behavioral and Brain Sciences*, 36(4), 329–47.  
52  
53 <https://doi.org/10.1017/S0140525X12001495>

1 Rhythmic training improves temporal conversational abilities in children with hearing loss

2  
3  
4 Port, R. F. (2003). Meter and speech. *Journal of Phonetics*, 31(3–4), 599–611.

5  
6 <https://doi.org/10.1016/J.WOCN.2003.08.001>

7  
8  
9 Przybylski, L., Bedoin, N., Krifi-Papoz, S., Herbillon, V., Roch, D., Léculier, L., ... Tillmann,  
10  
11 B. (2013). Rhythmic auditory stimulation influences syntactic processing in children  
12  
13 with developmental language disorders. *Neuropsychology*, 27(1), 121–31.

14  
15 <https://doi.org/10.1037/a0031277>

16  
17  
18 Rammsayer, T., & Altenmüller, E. (2006). Temporal Information Processing in Musicians  
19  
20 and Nonmusicians. *Music Perception*, 24(1), 37–48.

21  
22 <https://doi.org/10.1525/mp.2006.24.1.37>

23  
24  
25 Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature.

26  
27 *Psychonomic Bulletin & Review*, 12(6), 969–992. <https://doi.org/10.3758/BF03206433>

28  
29  
30 Repp, B. H. (2010). Sensorimotor synchronization and perception of timing: Effects of music  
31  
32 training and task experience. *Human Movement Science*, 29(2), 200–213.

33  
34 <https://doi.org/10.1016/j.humov.2009.08.002>

35  
36  
37  
38 Roy, A. T., Scattergood-Keeper, L., Carver, C., Jiradejvong, P., Butler, C., & Limb, C. J.  
39  
40 (2014). Evaluation of a Test Battery to Assess Perception of Music in Children With  
41  
42 Cochlear Implants. *JAMA Otolaryngology-- Head & Neck Surgery*, 140(6), 1–8.

43  
44 <https://doi.org/10.1001/jamaoto.2014.341>

45  
46  
47 Sares, A. G., Foster, N. E. V., Allen, K., & Hyde, K. L. (2018). Pitch and Time Processing in  
48  
49 Speech and Tones: The Effects of Musical Training and Attention. *Journal of Speech*

50  
51 *Language and Hearing Research*, 61(3), 496. [https://doi.org/10.1044/2017\\_JSLHR-S-](https://doi.org/10.1044/2017_JSLHR-S-)

52  
53  
54 17-0207

- 1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 Schön, D., & Tillmann, B. (2015). Short- and long-term rhythmic interventions: perspectives  
5 for language rehabilitation. *Annals of the New York Academy of Sciences*, 1337(1), 32–  
6 39. <https://doi.org/10.1111/nyas.12635>  
7  
8  
9  
10  
11 Schultz, B. G., O'Brien, I., Phillips, N., & McFarland, D. H. (2016). Speech rates converge in  
12 scripted turn-taking conversations. *Applied Psycholinguistics*, 37, 1201–1220.  
13 <https://doi.org/10.1017/S0142716415000545>  
14  
15  
16  
17  
18 Sebanz, N., & Knoblich, G. (2009). Prediction in Joint Action: What, When, and Where.  
19 *Topics in Cognitive Science*, 1(2), 353–367. <https://doi.org/10.1111/j.1756->  
20 [8765.2009.01024.x](https://doi.org/10.1111/j.1756-8765.2009.01024.x)  
21  
22  
23  
24  
25 Stabej, K. K., Smid, L., Gros, A., Zargi, M., Kosir, A., & Vatovec, J. (2012). The music  
26 perception abilities of prelingually deaf children with cochlear implants. *International*  
27 *Journal of Pediatric Otorhinolaryngology*, 76(10), 1392–400.  
28 <https://doi.org/10.1016/j.ijporl.2012.07.004>  
29  
30  
31  
32  
33  
34  
35 Street, R. (1984). Speech convergence and speech evaluation in fact-finding interviews.  
36 *Human Communication Research*, 11(2), 139–169. <https://doi.org/10.1111/j.1468->  
37 [2958.1984.tb00043.x](https://doi.org/10.1111/j.1468-2958.1984.tb00043.x)  
38  
39  
40  
41  
42 Street, R. L., & Cappella, J. N. (1989). Social and linguistic factors influencing adaptation in  
43 children's speech. *Journal of Psycholinguistic Research*, 18(5), 497–519.  
44 <https://doi.org/10.1007/BF01067313>  
45  
46  
47  
48  
49 Street, R. L., Street, N. J., & Van Kleek, A. (1983). Speech convergence among talkative and  
50 reticent three year-olds. *Language Sciences*, 5, 79–96. <https://doi.org/10.1016/S0388->  
51 [0001\(83\)80015-1](https://doi.org/10.1016/S0388-0001(83)80015-1)  
52  
53  
54  
55  
56  
57  
58  
59  
60

- 1 Rhythmic training improves temporal conversational abilities in children with hearing loss  
2  
3  
4 Timm, L., Agrawal, D., C. Viola, F., Sandmann, P., Debener, S., Büchner, A., ... Wittfoth, M.  
5  
6 (2012). Temporal Feature Perception in Cochlear Implant Users. *PLoS ONE*, 7(9),  
7  
8 e45375. <https://doi.org/10.1371/journal.pone.0045375>  
9  
10  
11 Torppa, R., Huotilainen, M., Leminen, M., Lipsanen, J., & Tervaniemi, M. (2014). Interplay  
12  
13 between singing and cortical processing of music : A longitudinal study in children with  
14  
15 cochlear implants Interplay between singing and cortical processing of music : A  
16  
17 longitudinal study in children with cochlear implants. *Frontiers in Psychology*,  
18  
19 5(December), 1–16. <https://doi.org/10.3389/fpsyg.2014.01389>  
20  
21  
22 Torppa, R., Salo, E., Makkonen, T., Loimo, H., Pykäläinen, J., Lipsanen, J., ... Huotilainen,  
23  
24 M. (2012). Cortical processing of musical sounds in children with Cochlear Implants.  
25  
26 *Clinical Neurophysiology*, 123(10), 1966–1979.  
27  
28 <https://doi.org/10.1016/j.clinph.2012.03.008>  
29  
30  
31  
32 Valdesolo, P., Ouyang, J., & DeSteno, D. (2010). The rhythm of joint action: Synchrony  
33  
34 promotes cooperative ability. *Journal of Experimental Social Psychology*, 46(4), 693–  
35  
36 695. <https://doi.org/10.1016/j.jesp.2010.03.004>  
37  
38  
39 van der Steen, M. C. M., & Keller, P. E. (2013). The ADaptation and Anticipation Model  
40  
41 (ADAM) of sensorimotor synchronization. *Frontiers in Human Neuroscience*, 7(June),  
42  
43 253. <https://doi.org/10.3389/fnhum.2013.00253>  
44  
45  
46 Vuust, P., Pallesen, K. J., Bailey, C., van Zuijen, T. L., Gjedde, A., Roepstorff, A., &  
47  
48 Østergaard, L. (2005). To musicians, the message is in the meter pre-attentive neuronal  
49  
50 responses to incongruent rhythm are left-lateralized in musicians. *NeuroImage*, 24(2),  
51  
52 560–4. <https://doi.org/10.1016/j.neuroimage.2004.08.039>  
53  
54  
55  
56 Wilson, M., & Wilson, T. P. (2005). An oscillator model of the timing of turn-taking.  
57  
58  
59  
60

1 Rhythmic training improves temporal conversational abilities in children with hearing loss

2  
3 *Psychonomic Bulletin & Review*, 12(6), 957–68. Retrieved from

4 <http://www.ncbi.nlm.nih.gov/pubmed/16615316>

5  
6  
7  
8 Wong, C. L., Ching, T. Y. C., Cupples, L., Button, L., Leigh, G., Marnane, V., ... Martin, L.

9 (2017). Psychosocial Development in 5-Year-Old Children With Hearing Loss Using

10 Hearing Aids or Cochlear Implants. *Trends in Hearing*, 21, 233121651771037.

11 <https://doi.org/10.1177/2331216517710373>

12  
13  
14  
15  
16  
17  
18 Yee, W., Holleran, S., & Riessjones, M. (1994). Sensitivity to event timing in regular and

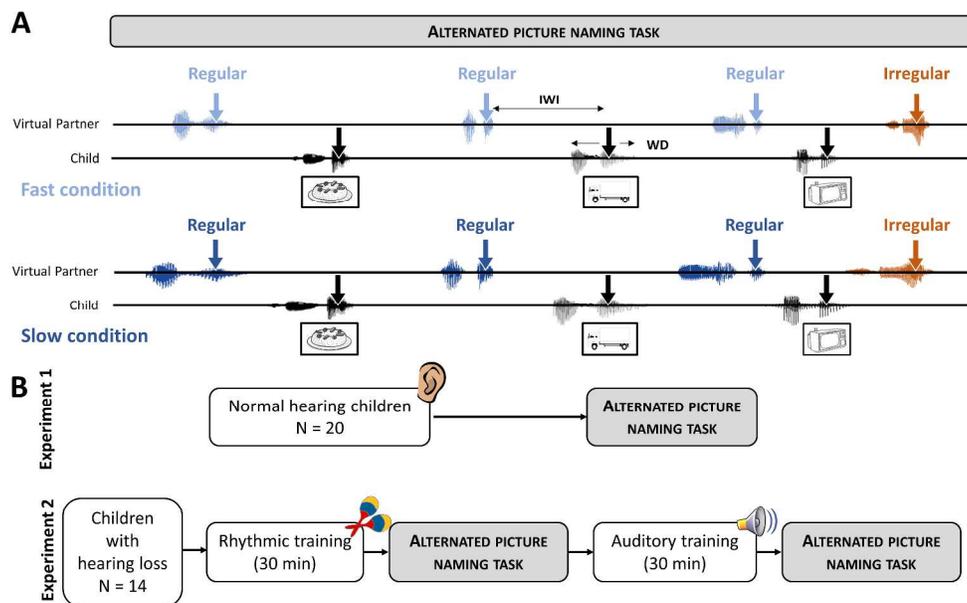
19 irregular sequences: Influences of musical skill. *Perception & Psychophysics*, 56(4),

20 461–471. Retrieved from <https://link.springer.com/content/pdf/10.3758/BF03206737.pdf>

21  
22  
23  
24  
25 Zarco, W., Merchant, H., Prado, L., & Mendez, J. C. (2009). Subsecond Timing in Primates:

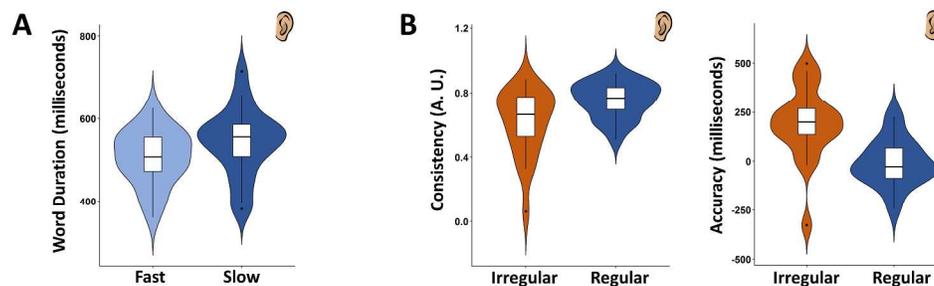
26 Comparison of Interval Production Between Human Subjects and Rhesus Monkeys.

27  
28  
29  
30 *Journal of Neurophysiology*, 102(6), 3191–3202. <https://doi.org/10.1152/jn.00066.2009>



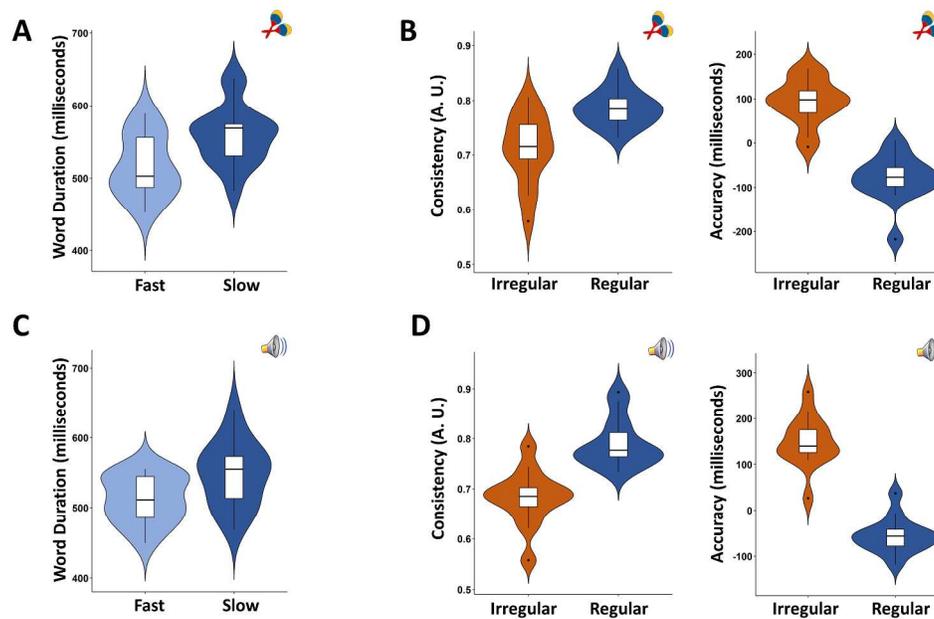
**Figure 1. Task and procedure.** A. Schematic representation of the task. The virtual partner pronounces isolated words at *regular* (blue, 2000 ms) or *irregular* (red, 1600 ms) intervals. The child names the objects presented on the screen in alternation with the virtual partner. The speech rate of the virtual partner can be *fast* (light blue, top panel) or *slow* (dark blue, bottom panel). The vertical arrows indicate the p-center placement of the words. IWI stands for Inter Words Intervals, namely the distance between the virtual partner p-center and the child p-center. WD stands for Words Duration, namely the duration of the words pronounced by the child. B. Schematic representation of the procedure. Normal hearing (NH) children ran the task once and children with hearing loss (HI) ran the task twice (order was counterbalanced). For all figures, the ear represents children with normal hearing, the maracas represent children with hearing loss after rhythmic training, and the loudspeaker represents children with hearing loss after auditory training.

340x209mm (300 x 300 DPI)



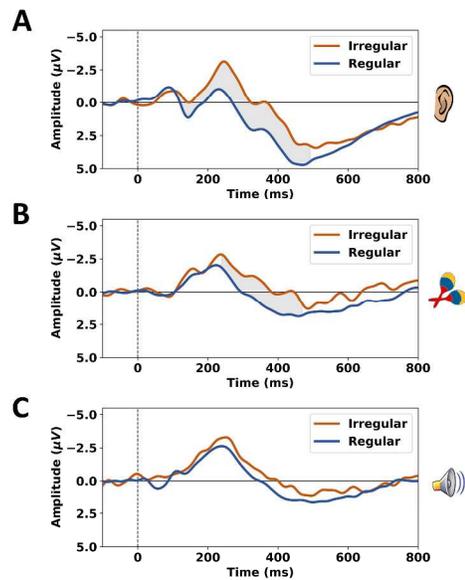
**Figure 2. Behavioral results for NH children.** A. Convergence results. Effect of the virtual partner's speech rate on mean word duration in the fast and slow conditions. B. Accommodation results. Effect of the regularity of alternation on children's stress placement. Left panel depicts the consistency of stress placement, represented by the vector length (from 0 to 1). Higher values represent better performances. Right panel depicts the accuracy of stress placement. Time zero represents a stress placement at the expected time. Positive values represent late responses, and negative values represent early responses.

340x209mm (300 x 300 DPI)



**Figure 3. Behavioral results for HI children.** A. Convergence results following a 30-min rhythmic training. Effect of the virtual partner speech rate on mean word duration in the fast and slow conditions. B. Accommodation results following a 30-min rhythmic training. Effect of the regularity of alternation on children stress placement. Left panel depicts the consistency of stress placement, represented by the vector length (from 0 to 1). Higher values represent better performances. Right panel depicts the accuracy of stress placement. Time zero represents a stress placement at the expected time. Positive values represent late responses, and negative values represent early responses. C-D. Convergence and accommodation results following a 30-min auditory training.

340x209mm (300 x 300 DPI)



**Figure 4. Electrophysiological (EEG) results.** Grand average of Event Related Potentials for regular and irregular trials. Time zero is the onset of the word pronounced by the virtual partner. Shaded areas represent significant time clusters ( $p < .05$ ). A. NH children. B. HI children after rhythmic training. C. HI children after auditory training.

340x209mm (300 x 300 DPI)