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Abstract

This study investigates temporal adaptation in speech interaction in children with normal hearing and in children with cochlear implants (CIs) and/or hearing aids (HAs). We also address the question of whether musical rhythmic training can improve these skills in children with hearing loss (HL). Children named pictures presented on the screen in alternation with a virtual partner. Alternation rate (fast or slow) and the temporal predictability (match vs mismatch of stress occurrences) were manipulated. One group of children with normal hearing (NH) and one with HL were tested. The latter group was tested twice: once after 30 minutes of speech therapy and once after 30 minutes of musical rhythmic training. Both groups of children (NH and with HL) can adjust their speech production to the rate of alternation of the virtual partner. Moreover, while children with normal hearing benefit from the temporal regularity of stress occurrences, children with HL become sensitive to this manipulation only after rhythmic training. Rhythmic training may help children with HL to structure the temporal flow of their verbal interactions.

Keywords

Hearing loss; Children; Temporal accommodation; Speech production; Interaction; Rhythmic training.

Abbreviations

NH, normal hearing; HL, hearing loss; P-center, perceptual center; IWI, inter-word-interval; ITI, inter-turn-interval; CI, cochlear implant; HA, hearing aid.

1. Introduction

Conversation requires that speakers accommodate to the verbal behavior of their conversational partner. This accommodation can alter the content (e.g. semantic system, Garrod & Anderson, 1987), the form of the exchange (e.g. intensity, Natale, 1975) or temporal aspects of the conversation (e.g., turn-taking, speaking rate, Beňuš, Gravano, & Hirschberg, 2011; Street, 1984). Generally, accommodation can lead to greater similarity of interlocutors' verbal patterns (e.g., Abney, Paxton, Dale, & Kello, 2014). It also plays an important role in enhancing mutual comprehension (Garrod and Pickering, 2004) and cooperation (Manson et al., 2013), and in reducing the social distance between interlocutors (Giles et al., 1991). In particular *temporal* accommodation between interlocutors, that is mutual adaptation of temporal structure (speech rate, turn-timing), is associated with positive perception (pleasantness) of a conversation (Warner et al., 1987). This type of accommodation evolves from very early on, in the interactions between infants (4 months) and their mothers (Jaffe et al., 2001). Importantly, temporal accommodation implies the capacity of interlocutors to *anticipate* various temporal characteristics of the partner's speech, such as the time of important discourse units, ends of utterances or turns (Garrod and Pickering, 2015). Temporal predictions aid interlocutors to "be on time" with their own verbal production, warranting a fluent verbal exchange and sustaining the flow of interaction.

Anticipatory processes involved in the development of conversational skills were already found in children as young as three years using eye tracking (Casillas and Frank, 2013). When watching a dialogue, three-year olds shifted their gaze onto the next speaker although the current speaker had not yet completed his turn. These results indirectly show that children develop early anticipatory abilities inherent to the conversation.

Hilbrink and collaborators (2015) obtained a more direct measure of these abilities by analyzing dialogues between mothers and children aged from 3 to 18 months. Their analysis revealed that temporal patterns of speech turns of mother-infant conversations (5 months) were similar to those found in adults (i.e., with little overlap of vocalizations and a small time interval between two turns). However, temporal accommodation and development of anticipatory skills in the production of children at verbal age await further clarification.

In clinical populations, it has been shown that using rhythmic cues and training can enhance temporal predictions in speech and thereby, may aid temporal accommodation in conversation. For example, patients with dysarthria (Liss et al., 2009) display irregular vocalic and consonantal segment durations altering speech rate and impacting conversational abilities. However, regular stress distributions in the speech of an interlocutor, allowing for enhanced temporal predictions, can help dysarthric patients to better accommodate to the speech of their conversational partner (Späth et al., 2016). Other clinical studies have highlighted that verbal and non-verbal rhythmic training, in particular by combining auditory and motor stimulation, can have positive effects in patients suffering from language disorders involving temporal deficits. For example, patients with non-fluent aphasia, improved their speech production (i.e. articulatory quality) when speech was accompanied by a regular pulse (Stahl, Kotz, Henseler, Turner, & Geyer, 2011). Rhythmic auditory cues accompanying speech can also enhance fluency in children and adults who stutter (Andrews et al., 1982). Children with SLI and dyslexia improved their grammatical judgments after listening to a regular prime (compared to an irregular prime, Przybylski et al., 2013). Children with dyslexia improved their phonological and reading abilities after an active musical training and this improvement in speech abilities was correlated with an improvement in their rhythmic abilities (Flaugnacco et al., 2015). Children with non-verbal autism spectrum disorders increased the range and the complexity of their vocal productions, after using an audio-motor training (15 minutes, 5 times a week during 8 weeks) as an intervention-program (Wan et al., 2011). These examples show that listening to regular rhythms or training rhythmic skills helps patients who suffer from deficits in temporal processing to better encode and predict the temporal structure of speech.

A particularly vulnerable population, with regard to the role of temporal predictions for their communicative skills, are children with hearing loss (HL). Children with cochlear implants (CIs) and/or hearing aids (HAs) show high variability in spoken language achievement and difficulties in communicational skills compared to children with normal hearing (NH) (van Wieringen and Wouters, 2015). Pragmatic skills develop relatively late in children with hearing loss using both speech and sign language, compared to children with NH (Bebko et al., 2003). Studies in children with HL describe inappropriate use of pragmatic features in speech turns (Most et al., 2010), greater presence of silences, communication breakdowns (Tye-Murray, 2003) and excessively long speech turns (Toe and Paatsch, 2013), eventually reducing the smoothness and balance of verbal exchanges.

These studies on pragmatic skills in children with HL clearly suggest conversational difficulties but miss a link with more general temporal processing deficits. Interestingly, the few studies addressing temporal prediction and processing in children with HL have been carried out in the music domain. While children with CIs or HAs are able to discriminate rhythmic patterns (Innes-Brown et al., 2013) children with CIs are less precise than children with NH (Stabej et al., 2012, Roy et al., 2014). Electrophysiological studies using the mismatch negativity protocol (MMN) show that children with CIs are less sensitive to temporal manipulation of a regular auditory structure compared to NH children (Torppa et al., 2012, Petersen et al., 2015). Interestingly, it was recently shown that, in a sentence repetition task, musical rhythmic priming of speech, by engaging temporal predictions, facilitated phoneme and word perception and production abilities of children with CIs and HAs, (Cason et al., 2015b).

In light of these findings, we wanted to test whether training temporal prediction capacities in children with HL via musical rhythm may impact their communication and accommodation skills in production. More precisely, the aims of the present study were twofold. First, focusing on children with NH, we investigated how rhythmic predictability of turn-taking impact on temporal accommodation skills at 5-6 years of age. Second, from a more clinical standpoint, we examined the hypothesis that rhythmic training influences these skills in French speaking children with HL wearing cochlear implants (CIs) and/or Hearing Aid (HAs). Indeed, CI technology can deliver temporal information better than spectral cues and several studies have shown a good performance of CI children in rhythmical musical tasks (e.g. Innes-Brown et al., 2013, Roy et al., 2014).

Inspired by adaptation studies with adults (Himberg et al., 2015; Kawasaki et al., 2013; Späth et al., 2016), we developed a child-friendly, novel procedure of a turn-taking paradigm (an “alternating picture naming task”) manipulating the difficulty of temporal anticipation required to perform the task. In a first Experiment, children with NH named pictures on the screen in alternation with a virtual partner. The temporal predictability of stress occurrences[1] and thus of the turns was manipulated as well as the alternation rate. We measured children's temporal adaptation and prediction skills by analysing the timing of the stressed syllables of words with respect to those of the virtual partner. We hypothesized that children should adopt a regular rhythm in their own turn-production (i.e., producing their words consistently with respect to the virtual partner, Himberg et al., 2015) depending on the alternation rate of the partner. Moreover, we hypothesized that altering the number of syllables per word and thus, lowering the predictability of time of stress occurrences should render

[1] We use the term “stress” throughout the manuscript in its broad sense (accent, emphasis), and not in terms of “lexical stress” which is not a feature of French, the native language of the participants in the present study.

the task more difficult and deteriorate children’s consistency in turn-taking. In a second Experiment, we used the same procedure to measure the impact of rhythmic training on speech production and more precisely on the temporal prediction abilities in speech in children with HL. Based on previous findings with other language impaired populations (Flaugnacco et al., 2015; Przybylski et al., 2013) we expected children with HL to benefit from rhythmic training in their adaptation skills, especially in the less predictable context.

2. Experiment 1

2.1. Material and methods

2.1.1. Participants

Sixteen children with NH were recruited from a *kindergarten* in Marseille. They were aged from 5 to 6 years old (mean age = *65* months, *SD* = 5 months) and were all native-speakers of French without any visual, speech, cognitive or hearing disorder. This experiment has been approved by the ethics committee Sud Méditerranée I (n°ID RCB: 2015-A01490-49). All children's parents signed a consent form.

2.1.2. Stimuli

One hundred sixty pictures from 16 taxonomic categories were selected from the French BD2I database (Cannard et al., 2005). Half of them depicted monosyllabic words, half were disyllabic. The selected pictures were named correctly by over 90 % of a normative sample of 3 to 8 year old children (monosyllabic words: mean score = 93.9 %, *SD*= 5.3 %; disyllabic words: mean score = 98.8 %, *SD*=1.6 %).

The picture names were recorded in a soundproof booth and they were spoken by a female native French speaker (henceforth, the virtual partner). An additional set of three words was recorded by an 8-year-old boy in order to construct a model for the alternated naming procedure. The perceptual centers of the syllables (*p-centers)* were estimated at 2/3 of the amplitude rise in the sound envelope using a semi automatic procedure (Cummins and Port, 1998). These estimated p-centers, described as being rhythmic anchor-points in speech, were used as points of reference for the adjustment of the interval between the words uttered by the adult virtual partner (i.e., the Inter-Turn-Interval, ITI). In disyllabic words, the p-center on the stressed syllable (i.e., the final syllable of each French accentual phrase) was chosen.

2.1.3. Procedure

Before the beginning of the Experiment, children were familiarized with the pictures. To this end, all the pictures used in the task were presented on a sheet and named by the participant to ensure the good identification and naming of pictures as well as the articulatory correctness of the words. After this familiarization phase, the participants were seated in front of a computer screen and instructed to name the pictures, displayed on the screen, in alternation with a virtual partner. On the screen, the child saw the pictures of the virtual partner (left-hand side) and his/her own pictures (right-hand side, see Figure 1) and was asked to name the picture after the virtual partner.

In order to manipulate temporal predictability of the turns, pairs of pictures were created by varying their syllable number ("word regularity") which modified the timing of words and their stress occurrences. In a highly predictable condition, the pair was *matched* in the number of syllables (i.e. the names of both pictures had the same number of syllables, mono- or disyllabic, respectively). In the less predictable condition, the pair was *mismatched* (i.e. one picture name was a monosyllabic word and the other a disyllabic word). Four blocks were built containing each 10 pairs of pictures in the *matched* condition (1 with monosyllabic words and 1 with disyllabic words) and 4 blocks of 10 pairs of pictures in the *mismatched* condition. Pictures in a given pair and pair order were carefully controlled in order to avoid semantic, categorical or phonological priming between words of the same pair or between two successive pairs. In a given block, the alternation rate was determined by the ITI of the virtual partner. It was either a fast rate (i.e., ITI of 2600 ms between the p-centers of two successive words of the virtual partner, see Figure 1) or slow (i.e., ITI of 3200 ms). This resulted in a 2 by 2 factorial design manipulating word regularity (matched or mismatched) and alternation rate (slow or fast) across blocks. The order of block presentation was counterbalanced across participants.

Each block started with 3 pairs of pictures that were named by the adult virtual partner in perfectly timed alternation with the voice of the 8-year-old boy in order to establish the rate of alternation in an implicit manner. Next,10 pairs of pictures were presented successively at the bottom of the screen in a scrolling manner and the child was instructed to name the pictures continuing the alternation. Children naturally tended to name the images in between the two successive pronunciations of the virtual partner. No information concerning when to pronounce the name of the image nor on word regularity and alternation rate were given to the child. A block was not interrupted even if the child misnamed or did not name a picture. The child was praised and encouraged to continue after completion of each block.

Stimuli delivery was programmed using the software *Presentation* (Neurobehavioral Systems 18.0). Pictures were displayed on a laptop screen (DELL Latitude E5530, screen resolution 1366 X 768). The volume for the voice of the virtual partner, delivered by a CREATIVE sound card (X-Fi 5.1) and two Sony loudspeakers (SRS A205), was adjusted for each child at a comfortable level. The naming performance of the participant was recorded with a head-mounted microphone (Sennheiser HSP) linked to a ZOOM H4n numeric recorder at a 44 Hz sampling rate.

2.1.4. Analysis

Inter-word-intervals between the child and the virtual partner and the relative timing of children's words to the words of the virtual partner were chosen as measures to evaluate temporal accommodation (Himberg et al., 2015). In order to determine the Inter-Word-Interval (IWI) between the virtual partner and the child, we estimated the distance of the p-centers of the stressed syllables within each pair of words as pronounced by the virtual partner and the child (see Figure 1). The IWI was chosen in order to evaluate children's accommodation to the different alternation rates (fast and slow). Intervals were excluded from analysis if the child made a hesitation (e.g., *euh*), erroneously placed an article before naming the object or spoke simultaneously with the virtual partner. This resulted in rejecting approximately 10% of word-intervals. Then, we analyzed the timing of children's stressed syllables in relation to those of the virtual partner. Because of the highly predictable rhythm of alternation, it was expected that children would anticipate the time of the words (their stressed syllable) of the virtual partner and, consequently, produce their own words (stressed syllables) in a stable temporal relationship to the virtual partner. This anticipatory behavior was confirmed in a pilot study on three children. A preferred and particularly stable temporal relation in rhythmic tasks requiring an action in response to a regular rhythmic auditory structure is the anti-phase (i.e., the mid-point between two periodically recurring auditory events; Repp, 2005; Volman & Geuze, 2000). Thus, the timing of the child's stressed syllables was analyzed, as a default, with respect to this 'expected' moment in time representative of a temporally perfectly regular alternation (i.e., half of the ITI of the virtual partner, notably, 1300 and 1600 ms after the p-center of the virtual partner for the slow and fast condition, respectively). The analysis is best performed using circular statistics (CircStat Toolbox, Berens, 2009). Thereby, each child's response is expressed as a vector in a circular space with respect to the expected moment in time (see Supplemental material, appendix A for more details). In this space, the angle represents the asynchrony (i.e., the distance between the child's production and the expected moment in time) and the length of the vector represents the *consistency* (i.e., the variability of the child's asynchrony across trials). Consistency is particularly useful to estimate the child's temporal accommodation skills as more consistent (less variable) performances are indicative of a better temporal representation of the reciprocal turn-structure. Previous to any statistical inference, the Rayleigh test was used to verify that performances were not randomly distributed in the circular space (that is not uniformly distributed). None of the children assessed in this study had a uniform distribution, showing that they had they had indeed produced the stressed syllables of the words in a consistent and anticipatory fashion with respect to the virtual partner's stresses.

2.2. Results

Three 2 x 2 repeated-measures analysis of variance (RM-ANOVA) with the factors Alternation rate (*fast* versus *slow*) and Word regularity (*matched* versus *mismatched* stress occurrences) and the mean Inter-Word-Interval and consistency as the dependent variables were performed.

IWI analyses revealed a main effect of alternation rate: children with NH showed longer intervals in the slow than in the fast alternation condition ($F(1, 15) = 24.99$, $p<.001$; see Fig. 2A). Consistency analyses showed that children were lass variable (i.e. more consistent) in the *fast* than in the *slow* condition (main effect of rate: $F(1, 15)=6.85$, $p=.019$; Fig. 2C). In addition, they showed a tendency to be less variable when the pairs of words had a regular instead of an irregular stress pattern (main effect of regularity: $F(1,15)=4.09$, $p=.061$; Fig. 2C).

2.3. Discussion

These findings show that children with NH, as young as 5 years of age, are sensitive to temporal variations (alternation rate and the timing of words' stressed syllables) in the turns of their interlocutor. As a matter of fact, results on IWI revealed that children are able to adapt their naming performance to the rate of the virtual partner. This temporal adaptation (fast vs. slow: Δ =157 ms) is an important finding as it demonstrates that children were not simply reacting to the visual stimulus they had to name, but they were indeed taking into account changes in the temporal pace of alternation. Hence, our task, as intended, was apt to measure children's temporal attunement abilities in a pseudo-interactive setting.

We also observed a trend for facilitated adaptation when sequences of words were more predictable in their timing properties, that is in the *matched* condition, wherein the child and the virtual words partner had the same number of syllables (i.e. the same stress patterns). Indeed, the mismatched condition seemed to perturb the dynamics of the interaction by slightly degrading the phase-locking between the child and the virtual partner. Note that a disyllabic word with a final stress needs to be initiated earlier than a monosyllabic word. Because the alternating naming task requires the child to anticipate the moment of her/his turn in relation to the naming interval of the virtual partner, changing the number of syllables of words may degrade anticipatory strategies or put higher demands on the anticipatory mechanism in general.

3. Experiment 2

In Experiment 2, we used the same paradigm in order to investigate the capacities of temporal accommodation in children with CIs or HAs following a speech therapy session and a rhythmic musical training.

We hypothesized that children with HL would benefit more strongly from a rhythmic training session in their adaptation skills, compared to a speech therapy session. This effect should be more evident in mismatched condition, that is when the temporal predictability of word exchanges was more difficult.

3.1. Material and methods

3.1.1. Participants

Fifteen children with HL aged from 5 to 9 years (mean age = 89 months, *SD* = 17 months) were recruited from the Centre d'Action Médicale Sociale Précoce in Marseille (children aged from 5 to 6 years) and the Service de Soutien à l'Education Familiale et à la Scolarisation in Marseille (children aged 6-9 years). Some of the children wore a unilateral CI, others wore bilateral CIs, some wore a cochlear implant (CI) in conjunction with a conventional hearing aid (HA) on the contralateral ear and others HAs. Even if CI delivers an electric signal to the auditory nerve versus an amplified acoustic signal for HA, users of both devices may benefit from a rhythmic training. The children suffered from different degrees of hearing loss (from profound to moderate, see Table

1 in the Supplemental material, appendix B ,where also the aided thresholds and other details of the subjects are given). They were all native French speakers, educated in oral communication, attended mainstream primary school, and were free from known visual, speech or other cognitive impairment. Data of two of the 15 participants had to be excluded as they were unable to perform the task. This experiment has been approved by the ethics committee (n°ID RCB: 2015-A01490-49, Sud Méditerranée I). All children's parents signed a consent form.

3.1.2. Stimuli, procedure and analyses

The stimuli, the task and data analyses were the same as in Experiment 1. However, participants of Experiment 2 performed the naming task twice. Once, the measure was taken 30 minutes after a training session focusing on musical rhythmic stimulation which was meant to enhance temporal prediction skills in children. The training included several rhythmic audio-motor games (for more details, see Supplemental material, appendix C). As a comparison, a 'baseline' measure was taken 30 minutes after a speech therapy session that focused on verbal stimulation in a classical speech therapy setting. Indeed, in order to avoid a general effect of training on arousal or mood that would render results difficult to interpret (Thompson et al., 2001) we opted for this 'baseline' measure instead of a non-stimulation baseline. Both types of stimulations lasted 30 minutes and used a playful and joyful setup. The 2 sessions were separated by one week on average and the order of stimulation was counterbalanced across children.

3.2. Results

Data were entered into a three 2x2x2 RM ANOVA with Alternation rate (*fast* versus *slow*), Word regularity (*matched* versus *mismatched stress occurrences*), and Training type (*speech therapy* versus *rhythmic training*) as within subject factors and IWI (Inter-Word-Interval) and consistency (i.e. regularity) dependent variables.

Analyses on the IWI revealed a main effect of alternation rate on mean IWI: children with HL produced longer IWI in the slow than in the fast condition ($F(1,12)=10.95$, $p=.006$). Consistency analyses showed that children with HL were generally more consistent in the *fast* than in the *slow* condition (consistency: $F(1,12) = 8.72$, $p = .012$.

As Fig. 3 shows, we found no main effect of regularity on consistency ($p=.414$) but an interaction effect of training type and word regularity ($F(1,12)=7.99$, $p=.015$).

3.3. <u>Discussion</u>

Children with HL were generally able to adapt their rate of production to the rate of the virtual partner and were generally more consistent in the *fast* than in the *slow* condition as NH children.

However, children with HL showed no differences in consistency when the pairs of words had a regular or an irregular number of syllables after the speech therapy session. However, and most importantly, after musical training, children with HL became more consistent in their alternation pattern in the matching than in the non-matching condition. This suggests that they were more sensitive to the temporal regularity of the speech exchanges after the rhythmic training. Note that (the younger) children with NH in Experiment 1 responded in a similar way (i.e., matched > mismatched stress occurrences), but without musical training.

4. General discussion

In sum, the present study showed that children with NH as young as 6 years of age were able to temporally anticipate and accommodate to the turn-structure of a virtual partner in a non-random way. Results showed that they were sensitive to the temporal predictability of turns and that they temporally adapted their speech production better to faster than slow turn rhythms. Children with HL, after having received speech or musical training also managed to perform the task and adapted better to fast than to slow turn rhythms. However, in contrast to the younger NH children, they did not benefit from more predictable turn-structure, unless they received musical rhythmic training. Most importantly, this is, to our knowledge, the first study to provide evidence that a rhythmic training of only 30 minutes may enhance the capacity of children with HL to accommodate to a temporally predictable flow of turn exchanges in an interactional setting. This effect points to potential benefits of rhythmic training on audio-motor anticipatory skills in children with HL. Rhythmic training may also have improved the extraction of regularities along the series of speech exchanges. By grouping discrete events (e.g. words) in a more hierarchical structure, children may have better perceived the metrical structure of the turns (i.e., the recurrence of stresses / syllables), allowing for a more precise temporal prediction of their own and their partner’s turns.

Previous work has shown that musical training in adults enhances connectivity within a dorsal network comprising the auditory and the motor cortex (Chen, Penhune, & Zatorre, 2008). This network plays an important role in auditory predictions (Schubotz, 2007) and attentional dynamics (Schroeder et al., 2010). There is a possibility that rhythmic training in children with HL may stimulate the sensori-motor dorsal pathway and thereby improve children’s abilities to adapt to a regular temporal structure (Vuust and Witek, 2014) or more generally improve their ability to perceive and understand rhythmical and metrical structure (Cason et al., 2015a).These different possibilities should be investigated in further detail in future studies.

Overall, our results are in line with previous studies showing that sensori-motor rhythmic training enhances auditory processing in different forms of language impairment at cortical and subcortical levels (Flaugnacco et al., 2015; Fujii & Wan, 2014; Tierney & Kraus, 2013). Concerning the sensorimotor rhythmic capacities of adults with CIs, their lack of synchronization capacity on a complex musical stimulus (Phillips-Silver et al., 2015) could be indicative of the fact that meter (i.e., the regular recurrence of a beat or accents) perception and / or production is underdeveloped in hearing loss. Our data in children with HL seem to confirm these previous findings in adults. Interestingly, similarly to adults listening to complex auditory stimuli, children with HL, even after a speech therapy session, do not take advantage of the temporal regularity of stress occurrences in our task, while children with NH do. As metrical perception is shaped by auditory experience (Hannon and Trehub, 2005), musical practice may refine this type of perception in both music (Geiser et al., 2010), and speech (Marie et al., 2011). Developing the perception of meter in children with hearing loss may thus improve their general temporal anticipatory skills and thus enhance their ability to adapt in simple as well as in more complex speech interaction contexts. Moreover, the enjoyment related to music training and more specifically the fact of being actively involved in synchronizing with somebody during 30 minutes, may also have enhanced children's engagement in the interactional task and improved their consistency after rhythmic training (Kirschner and Tomasello, 2009).

5. Conclusion, limitations and perspectives

This study presented a new task which allows for examining temporal adaptation in children at verbal age in an interactive situation with a virtual partner. Results showed the relevance of rhythmic musical training to improve temporal skills in children with HL. The future development of this task, including the use of a more adaptive virtual agent and more complex utterances going beyond the use of single words, will help us to better understand on which level of conversational coordination rhythmic musical training can impact the most (Phillips-Silver and Keller, 2012). As our study was confined to a very periodic structure of turns, future investigations may extend to other time-sensitive phenomena in less constrained speech interaction, such as speech convergence (Pardo, 2006) which could benefit interlocutors by mutually reducing cognitive load and facilitating prosocial behavior (Manson et al., 2013).

As the musical training session was conceived to focus on rhythmic skills and entrainment, it may have enhanced not only predictive skills, but also auditory processing in general. This may, in turn, have enhanced encoding of acoustic cues such as pitch, intensity and duration, that characterize stress patterns (Torppa et al., 2014). Overall, this work supports the idea that musical stimulation in general and sensori-motor rhythmic training in particular can be integrated in speech and language rehabilitation of children with HL. Further studies should also address a direct comparison of children with NH and HL, which was beyond the scope of this work. Our results are also encouraging from a clinical perspective. Speech therapists with an appropriate focused musical training could develop simple but recurrent rhythmic activities with their patients with HL. Moreover, these rhythmic activities could also be carried out in a group, which was not feasible in the context of this protocol that required individual testing immediately after the training session.

Acknowledgements

This work was supported by the Brain and Language Research Institute (BLRI, ANR-11-LABEX-0036 to C.H., S.F. and D.S.), the European Union Seventh Framework Program (FP7-PEOPLE-2012-IEF, n° 327586 to S.F.), and the LMU*excellent* program within the framework of the German excellence initiative (to S.F.).

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Figure legends

Figure 1. Representation of the time course of 2 trials of a fast alternation block. The thick rectangle indicates the current pair of pictures. The virtual partner names the pictures on the left (trial 1: knife fr.*couteau*), while the child has to name the pictures on the right (trial 1: baby, fr.*bébé*). Corresponding representation of the speech signal. The ticks indicate the location of the virtual partner p-centers (p 0, p 2600) and, for the child, the expected location of the child p-centers (p 1300, p

3900). The actual child p-centers, in this example, are indicated by an arrow and are slightly ahead the expected moment.

Figure 2. Panel A: Children's (NH) temporal accommodation with a virtual partner. Error bars represent the standard error of the mean. Left: mean IWIs in seconds between the p-centers of the stressed syllables of the child and those of the virtual partner in the Slow and Fast conditions. Right: Consistency (vector length) of the child's word productions as a function of word regularity. Panel B: Temporal accommodation with a virtual partner in children with HL. Left: Mean IWIs in seconds between the p-centers of the child and those of the virtual partner in the Slow and Fast conditions. Right: Consistency (vector length) of the child's word production as a function of word regularity in both training conditions. P-values are results of post-hoc tests.

<u>Supplemental material</u>

Appendix A: Measuring consistency with circular statistics.

Appendix B: Details on the children with hearing loss

Appendix C: Rhythmic musical training