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Transfer of sensorimotor learning reveals phoneme representations in preliterate children

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Abstract

Reading acquisition is strongly intertwined with phoneme awareness that relies on implicit phoneme representations. We asked whether phoneme representations emerge before literacy. We recruited two groups of children, 4 to 5-year-old preschoolers (N=29) and 7 to 8-year-old schoolchildren (N=24), whose phonological awareness was evaluated, and one adult control group (N=17). We altered speakers' auditory feedback in real time to elicit persisting pronunciation changes, referred to as auditory-motor adaptation or learning. Assessing the transfer of learning at phoneme level enabled us to investigate the developmental time-course of phoneme representations. Significant transfer at phoneme level occurred in preschoolers, as well as schoolchildren and adults. In addition, we found a relationship between auditory-motor adaptation and phonological awareness in both groups of children. Overall, these results suggest that phoneme representations emerge before literacy acquisition, and that these sensorimotor representations may set the ground for phonological awareness.

1. Introduction

During reading acquisition, children learn correspondences between graphemes (i.e. letters or sets of letters) and speech sounds, namely phonemes (Share, 1995). Literacy has been suggested to reorganize phonological representations (Pattamadilok, Knierim, Kawabata Duncan, & Devlin, 2010) in a way that may depend on the writing system (Wang, Wong, Wang, & Chen, 2017). Learning to read is closely related to phoneme awareness which is the capacity to explicitly identify and manipulate phonemes (Ziegler & Goswami, 2005). While phoneme awareness strongly predicts reading acquisition success (Melby-Lervåg, Lyster, &

Hulme, 2012), learning to read may in turn be essential in the development of phoneme awareness (Morais, Cary, Alegria, & Bertelson, 1979). Thus there is probably a mutual facilitation between these two skills (Castles & Coltheart, 2004). Phoneme awareness is often claimed to rely on implicit phoneme representations (Fowler, 1991; Swan & Goswami, 1997). Therefore, a key question is: do these implicit phoneme representations emerge during reading acquisition in children, or prior to it?

In an emergentist view, the representations used by children when producing **early** words are **usually** word templates (Vihman & Croft, 2007). Then representations gradually become more fine-grained and segmental (Cristia & Hallé, 2012). This evolution, interestingly related to vocabulary growth, may continue until middle childhood (Fowler, 1991; Nittrouer, Studdert-kennedy, & McGowan, 1989; Walley, Metsala, & Garlock, 2003). Although the term phonological representations – i.e. representations of phonological units, encompassing phonemes - has been much used, it is difficult to find measures probing phonological representations independently of other cognitive skills (Ainsworth, Welbourne, & Hesketh, 2016; Boada & Pennington, 2006) .

We argue that phonological representations are essentially sensorimotor representations (Schwartz, Basirat, Ménard, & Sato, 2012; Tourville & Guenther, 2011). These representations involve both speech perception and production, associating sensory cues with motor characteristics, within categories. This view is consistent with the general developmental framework based on the dynamic systems theory (Smith & Thelen, 2003), proposing that representations are the manifestation of interactions between sensorimotor processes. This sensorimotor view of phonological representations may find support in the literature on dyslexia, which is often associated with phonological awareness deficits (Goswami, 2006). Indeed, in addition to various deficits in auditory processing (Boets et al., 2011; Noordenbos & Serniclaes, 2015) and implicit motor learning (Stoodley, Harrison, &

Stein, 2006), dyslexia has been related to sensorimotor integration difficulties (Viana, Razuk, de Freitas, & Barela, 2013). Consistent with this finding, dyslexia has been associated to different sensorimotor responses to auditory perturbations compared to controls (van den Bunt et al., 2018 a; van den Bunt et al., 2017). Moreover, in typically developing preliterate children, reading-related skills (including phonological awareness) were found to be correlated with the properties of sensorimotor representations, as probed by an auditory-motor learning paradigm (van den Bunt et al., 2018 b).

The auditory-motor learning paradigm consists of altering in real time the auditory feedback of a speaker producing an utterance (Houde & Jordan, 1998). For instance, the perturbation makes a vowel sound like another vowel. Speakers usually adapt to the perturbation in that they compensate for it by changing their pronunciation. This change persists even after feedback is returned to normal, revealing a change in the sensorimotor representation of the utterance, hereafter referred to as “the training word”. Whether this representation is defined at phonemes level can be probed by assessing generalization, also called transfer of learning (Cai, Ghosh, Guenther, & Perkell, 2010; Caudrelier, Schwartz, Perrier, Gerber, & Rochet-Capellan, 2018; Houde & Jordan, 1998; Rochet-Capellan, Richer, & Ostry, 2012). If the change in pronunciation transfers from the training word to another word produced under normal or masked feedback, it reveals the existence of a common representation shared by these words. Testing generalization as a mean to probe representations has been used in speech perception literature (McQueen, Norris, & Cutler, 2006; Mitterer, Reinisch, & McQueen, 2018; Mitterer, Scharenborg, & McQueen, 2013). To our knowledge, transfer of auditory-motor learning has never been studied in children in speech production.

In the present study, we investigated whether children relied on phoneme representations in speech production before the acquisition of reading, and before the

emergence of phoneme awareness. We assessed transfer of adaptation at the phoneme level in preschoolers, in contrast with schoolchildren and adults. If such transfer occurs in preschoolers, then it can be assumed that phoneme representations in speech production emerge with speech experience rather than as a by-product of learning to read. We also tested whether robust auditory-motor adaptation is associated with higher phonological awareness in children, before and after reading acquisition, as shown by van den Bunt et al. (2018b) though only for preliterate children. Confirming such a link would reinforce the view that auditory-motor learning taps into phonological representations that underlie phonological awareness (PA).

2. Methods

2.1 Participants

Native speakers of Canadian French (N=70) were included in this study, of which 29 preschoolers (4- to 5-year-old, mean=4.9y, sd=0.6), 24 schoolchildren (7- to 8-year-old, mean=8.0y, sd=0.5), and 17 adults (mean=25y, sd=4). In addition to them, two preschoolers and one 8-year-old child participated but were excluded as they gave up or did not follow the task; another preschooler was excluded because of his high score in phoneme awareness (see in section 3.3 for more information). Written informed consent was given by adult participants and parents of children, in agreement with Ethics statements (ethics approval number 390_e_2017, Institutional Review Board of the Université du Québec à Montréal).

Subjects had no reported speech, language or hearing disorders, and were naive to the purpose of the experiment. All participants had to perform the same production task, which was followed for all children by a PA test. The total duration did not exceed 20 minutes in preschoolers and 30 minutes in schoolchildren.

2.2 Phonological awareness test

During the PA test, all children performed a rhyme judgment task, a syllable deletion task in CVCV pseudo-words, and a phoneme deletion task in CVC. The second-grade group also performed phoneme deletions in CCV, syllable inversions in CVCV, and phoneme inversions in CV and VC. The rhyme judgment task was taken from a French Canadian test for preschoolers (Lefebvre & Sutton, 2008). The other tasks were taken from BELEC (Mousty, Leybart, Alegria, Content, & Morais, 1994), using blocks to represent phonological units in order to ease children's comprehension of the task, as specified in Lefebvre & Sutton (2008).

2.3 Auditory-motor adaptation task

2.3.1 Equipment, task, and auditory perturbation

Speakers were instructed to name pictures presented on a monitor, speaking in a natural way. They heard their own voice mixed with speech shaped noise in headphones. During the training phase, the vowel /e/ was shifted towards /ɛ/ in the auditory feedback, by increasing F1 by 27% and decreasing F2 by 10% using Audapter (Cai, Boucek, Ghosh, Guenther, & Perkell, 2008; Caudrelier, Schwartz, et al., 2018). Audapter formants prior values (*fn1* and *fn2* parameters) were adjusted for each speaker based on formants measured in prerecorded productions of /pe/.

2.3.2 Experimental procedure

The training utterance was the pseudoword /pe/ and the test utterance to assess transfer was the French word 'épée' (/epe/), which means "sword". These choices were consistent with our previous study (Caudrelier, Schwartz, et al., 2018). Importantly, the test utterance was a real word well known by 4-year-old children and easy to prompt by a picture, to make sure that all children would remember it when they would have to produce it. Speakers were

trained to provide the expected utterance from adequate pictures (a fictional character called “pé” /pe/ for training, and a picture of a sword for testing).

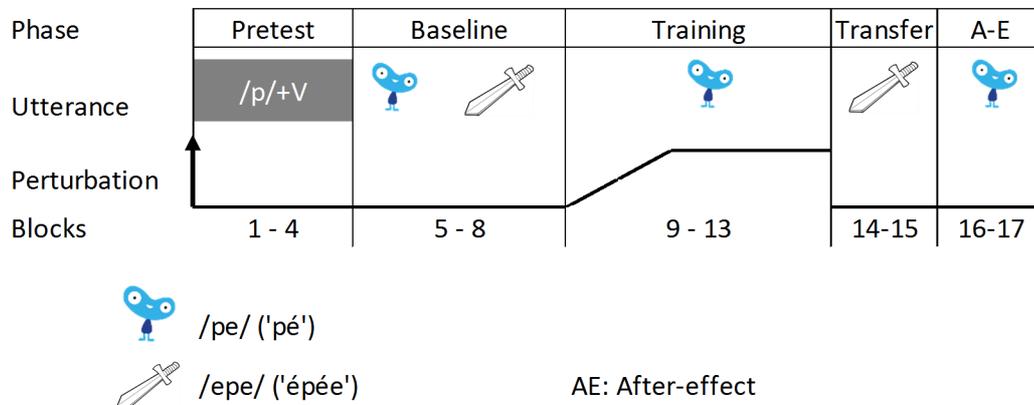


Figure 1: Auditory-motor adaptation procedure

The procedure consisted of 5 phases (Figure 1) made of blocks of 10 repetitions, as follows.

(1) In the pretest (blocks 1 to 4, without perturbation) speakers pronounced monosyllabic words (/pa/, /pi/, /pu/, /pɛ/) and the training utterance (/pe/). (2) In the baseline (blocks 5 to 8, without perturbation) speakers produced /pe/ and /epe/ twenty times each. (3) In the training phase, the perturbation was gradually introduced during blocks 9 and 10, in four steps, and then held at its maximum (blocks 11 to 13), while speakers pronounced the training utterance /pe/. When the perturbation stopped, (4) speakers pronounced /epe/ in the transfer phase (blocks 14 and 15), and speakers repeated /pe/ again (5) in the after-effect phase (blocks 16 and 17).

2.4 Predictions

Consistent with previous observations (Caudrelier, Perrier, Schwartz, & Rochet-Capellan, 2018; Caudrelier, Schwartz, et al., 2018), we expected significant transfer at both syllabic and phonemic levels (i.e. in both /e/ of /epe/) in adults. We also predicted that: (H1) if phoneme representations emerge as a by-product of reading acquisition, then transfer pattern

should be similar in 8-year-old children and in adults, whereas in 4-year-old children transfer should occur only at a syllabic level (from /pe/ to /pe/ in /epe/) but not at the phoneme level (to the first /e/ of /epe/). Conversely, (H2) if phoneme representations have already emerged in 4-year-olds (before reading acquisition) some transfer from /pe/ to /e/ should occur in preschoolers. Finally, (H3) if auditory-motor adaptation and transfer probe representations that set the ground for phonological awareness development, then we should find a relationship between adaptation and PA scores.

2.5 Measurements

Formants were measured in a 30-ms window in the middle of the vowel as in (Caudrelier, Schwartz, et al., 2018) and expressed in Barks (Schroeder, Atal, & Hall, 1979). Then, adaptation and transfer magnitudes were expressed as the percentage of change in (F2-F1) vs. the average (F2-F1) in the baseline, in the same utterance and the same speaker:

$$\left(\frac{(F2 - F1)_{trial}}{\text{mean}(F2 - F1)_{baseline}} - 1 \right) * 100$$

2.6 Statistical analysis

The analyses were carried out using R software (version 3.2.0 - R Development Core Team, 2016).

2.6.1 Linear Mixed Models.

Adaptation, transfer and after-effect magnitude were modeled by Linear Mixed Models (LMM) using a backward deletion approach. Potential autocorrelation and differences in variance across groups were taken into account (Liu, Cripe, & Kim, 2009). Post hoc tests were adjusted for multiple comparisons (Hothorn, Bretz, & Westfall, 2008). A first LMM modeled adaptation (block 13) and after-effect (block 16) with *age_group*, *phase* (training vs after-effect) and *trial* as fixed factors. Transfer of adaptation was assessed for adapted

subjects, considering that if there was no adaptation there could not be transfer. Adapted speakers were detected by a non-parametric Wilcoxon test checking whether (F2-F1) in the last 20 trials of the training phase was significantly different from (F2-F1) in the 20 trials of the baseline. In another LMM which included only adapted speakers, *age_group*, *syllable* (1st vs 2nd syllable of /epe/) and *trials* were the fixed factors to model transfer of adaptation (blocks 14 and 15).

2.6.2 Relationship with phonological awareness.

To assess whether sensorimotor behaviors are possible predictors of PA, the relationships between PA and (1) adaptation and (2) transfer were assessed with a Beta regression using *Betareg* function from R package *betareg* (Cribari-Neto & Zeileis, 2010). The regression modeled PA¹ with *age_group*, adaptation (adapters vs. non-adapters) and their interactions. Two variants of PA scores were evaluated: the score on the common part of the test between 4- and 8-year-olds to examine the effect of *age_group* without any bias related to the test, and the score on the whole test, which differed between age groups, to avoid ceiling effects in the 8-year-old group.

To assess the relationship between PA and transfer, PA score was modeled using the variables *age_group*, *syllable*, *transfer magnitude* and their interactions.

¹ PA score was expressed in proportion of correct response, therefore ranging from 0 to 1. A transformation was applied to avoid 0 and 1 values as required by the Beta regression. The transformation is $(y \cdot (n - 1) + 0.5)/n$, with n being the number of participants and y the initial value (Smithson & Verkuilen, 2006).

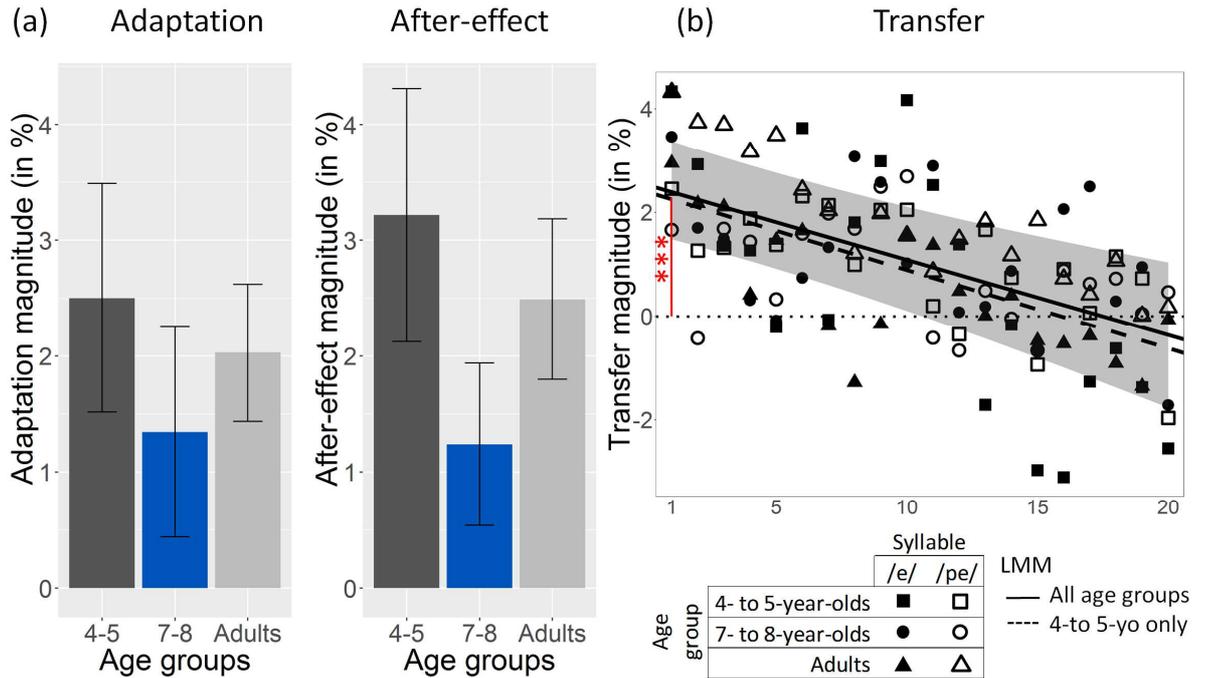


Figure 2: (a) Average adaptation and after-effect magnitudes by age groups in all speakers (preschoolers: N=29; schoolchildren: N=24; adults: N=17). Error bars represent standard errors. (b) Transfer magnitude by trial, by age group and by syllable in adapted speakers (preschoolers: N=11; schoolchildren: N=10; adults: N=12). Shaded area shows the 95% confidence interval of the linear mixed model for all age groups, and *** ($p < 0.001$) is related to the intercept in the same model.

3. Results

3.1 Adaptation and after-effect

The average magnitude of adaptation and after-effect is shown in Figure 2(a). It is similar across age groups. Indeed, the best model comprises only an interaction between phase and trial ($\text{Chisq}(1) = 5.14$; $p = 0.02$) but no age_group effect. Adaptation and after-effect magnitudes are significant, as shown by intercepts ($2.2\% \pm 0.5$; $z = 4.3$; $p < 0.001$ and 3.2%

± 0.5 ; $z=6.2$; $p<0.001$). Adaptation is stable ($-0.02\%/trial \pm 0.02$; $z=-0.81$; $p=0.9$) while after-effect significantly decreases over trials ($-0.09\%/trial \pm 0.03$; $z=-3.47$; $p=0.003$)².

11 preschoolers, 10 schoolchildren and 12 adults significantly adapted to the perturbation (hereafter, the “adapted speakers”).

3.2 Transfer of learning

The dynamics of transfer magnitude is shown in Figure 2(b). Transfer from /pe/ to /epe/ was equivalent across groups. The only fixed factor of the obtained model was trial ($\text{Chisq}(1)=14.2, p<0.0001$). Transfer was significantly above 0 at the beginning of the phase ($2.4\% \pm 0.5$; $z=5.1$; $p<0.001$). The slope was significantly negative ($-0.15\% \pm 0.03$; $z=-4.4$; $p<0.001$). When analyzing preliterate children only, we obtained the same model and transfer was still significant at the beginning of the phase ($2.3\% \pm 0.8$; $z=2.7$; $p=0.01$). Hence transfer occurred in all age groups at both syllable and phoneme levels.

3.3 Phonological awareness

Table 1 shows PA scores by subtask in both groups of children. All preschoolers got phoneme deletion scores, related to phoneme awareness, close to 0 – actually all at 0 except 1 at 20% and 1 at 30%). The child excluded from the analyses (see Section 2.1) had a score at 70%.

Phonological Awareness scores (in % of correct responses)		Preschoolers		Schoolchildren	
		mean	sd	mean	sd
Part 1	Rhyme judgement	58	25	94	7
	Syllable deletion	25	29	94	10
	Phoneme deletion in CVC	2	4	80	20
	Part 1 subtotal	31	17	90	9
Part 2	Phoneme deletion in CCV	/	/	78	21
	Syllable inversion	/	/	75	21
	Phoneme inversion	/	/	86	9
	Total score	31	17	84	10

² All full models output, as well as supplemental analyses including age as a continuous factor, can be found in the supplement.

Table 1: Phonological awareness scores in % of correct responses by age group and by subtask (preschoolers: N=29; schoolchildren: N=24).

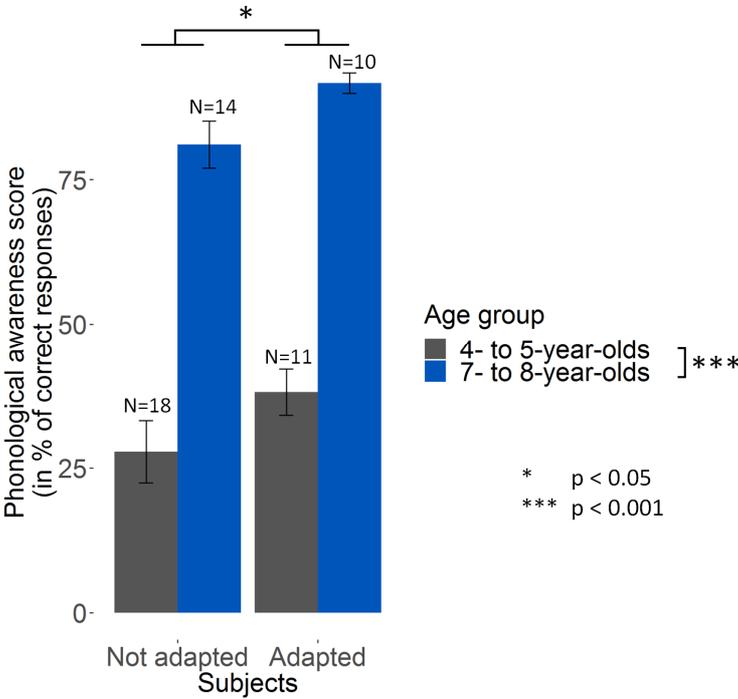


Figure 3: Bar chart of phonological awareness total score by age group and whether children adapted to the auditory perturbation or not.

Adapted vs non-adapted subjects. Figure 3 shows PA scores in children who adapted to the perturbation vs. non-adapted children (preschoolers: N=29; schoolchildren: N=24).

Regardless the score taken into account (part 1 or total score), there was a significant effect of both *age_group* and *adaptation* (adapted vs. not adapted) factors, and no interaction between them. Multiple comparisons (with part 1 scores) show that: scores in 8-year-olds were significantly higher than in 4-year-olds ($z=10.07$; $p<0.0001$); and scores were higher in adapted speakers than in non-adapted speakers ($z=2.25$; $p=0.047$). Score difference between adapters and non-adapters was even larger when using total scores ($z=2.68$; $p=0.0147$).

Transfer and PA. No relationship was found between transfer magnitude and PA scores in adapted speakers.

4. Discussion

Phoneme awareness, strongly intertwined with reading acquisition, relies on phoneme representations, which we assume to be sensorimotor representations (Schwartz et al., 2012). The present study was designed to determine whether these phoneme representations emerge before reading acquisition. These representations were probed using the paradigm of auditory-motor adaptation and transfer (Caudrelier, Schwartz, et al., 2018; Houde & Jordan, 1998).

Transfer at the phoneme level occurred in all age-groups, including the 4- to 5-year-old preschoolers, suggesting the existence of phoneme representations at this age. No evidence for age differences was found in the transfer pattern. In addition, as expected, phonological awareness (PA) tests indicate that preschoolers had some syllable awareness, but no or very little phoneme awareness (except one child that was excluded from the analysis). These observations suggest that phoneme sensorimotor representations emerge before the development of phoneme awareness, and before reading instruction starts, as already supported by Ventura, Kolinsky, Fernandes, Querido, & Morais, (2007).

We found no significant difference in the average adaptation magnitude between groups. This suggests that the representations underlying auditory-motor adaptation are established early in development whereas phonological awareness continues to develop over childhood. There might though be an age effect that was not found for statistical power reason. This adaptation pattern differs from Van den Bunt et al. (2018) study reporting lower adaptation in 5-year-old than in 7-year-old children. However, our observations are consistent with two previous studies in 4-year-olds and older children which report equivalent adaptation magnitude across ages (MacDonald, Johnson, Forsythe, Plante, & Munhall, 2012; Terband & van Brenk, 2015).

In both groups of children, average PA scores in adapted participants were significantly higher than average scores in non-adapted ones. This suggests that whether preschoolers adapt to the perturbation or not could be a predictor of later PA development, although a longitudinal study would be required to confirm this predictive role. These results extend the results by Van den Bunt et al. (2018) who found a relationship between adaptation magnitude and PA scores in preliterate children only.

The relationship observed between auditory-motor adaptation and PA at two different development stages may lead to several interpretations. First, it may reveal a direct connection between PA skills and underlying sensorimotor representations which the paradigm taps into. This link may also be driven by a third factor that would influence both auditory-motor adaptation and PA. This factor could be categorical perception (CP) which has been shown to influence both reading abilities and auditory-motor learning (Niziolek & Guenther, 2013, see also Shiller & Rochon, 2014). Yet PA is associated with spoken vocabulary growth (Walley et al., 2003), suggesting that speech production – and not only perception - is involved in representations underlying PA development (see also Vihman, 2017). Since CP arises generally in the first year of life while adaptation mechanisms may establish between 2 and 4 years of age (MacDonald et al., 2012), we rather suggest that CP pave the way for the development of phoneme sensorimotor representations, which then serve as foundations for phoneme awareness acquisition.

The present study used an auditory-motor adaptation and transfer paradigm to probe phonological representations in children. The results provide evidence for the emergence of phoneme representations before the apparition of phoneme awareness and reading instruction. They also underline connections between sensorimotor representations and higher-level skills (Smith & Thelen, 2003). Training sensorimotor processing may be considered to support reading acquisition. Future studies could probe phonological representations in dyslexic

people using the paradigm of auditory-motor learning transfer. This paradigm could also enable to explore how phonological representations of different languages relate to each other in multilingual speakers. Transfer of sensorimotor learning may thus turn out to be a valuable tool to study phonological representations and their development.

Supplementary material

Dataset can be found at: <https://doi.org/10.5281/zenodo.2645764>

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