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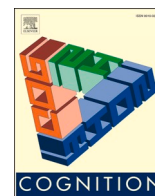
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The impact of alphabetic literacy on the perception of speech sounds[☆]

Régine Kolinsky^{a,b,*}, Ana Luiza Navas^c, Fraulein Vidigal de Paula^d, Nathalia Ribeiro de Brito^c, Larissa de Medeiros Botecchia^c, Sophie Bouton^e, Willy Serniclaes^{b,f}

^a Fonds de la Recherche Scientifique-FNRS (FRS-FNRS), Belgium

^b Unité de Recherche en Neurosciences Cognitives (Unescog), Center for Research in Cognition & Neurosciences (CRCN), Université Libre de Bruxelles (ULB), Belgium

^c Curso de Fonoaudiologia, Faculdade de Ciências Médicas da Santa Casa de São Paulo, School of Medical Sciences of Santa Casa de São Paulo, Brazil

^d Instituto de Psicologia, Universidade de São Paulo (USP), Brazil

^e Laboratoire Dynamique du Langage, CNRS, and Université Lyon 2 UMR 5596, France

^f INCC (Integrative Neuroscience and Cognition Center) CNRS and Université de Paris, France

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ABSTRACT

The aim of the present study was to evaluate the impact of literacy on phoneme perception. It built on previous research by using more controlled stimuli than in former studies and by independently examining the impacts of literacy and age on phoneme perception. Participants were adult and children beginning readers, and skilled adult readers. They were presented with identification and discrimination tasks, using a voicing continuum. In addition to examining their categorical perception of speech sounds and the precision of phonemic categories, participants' literacy level was carefully evaluated. The results confirmed that neither age nor literacy modulated categorical perception. However, level of literacy did have a significant impact on the precision of phonemic categories, which was independent from the influence of age.

1. Introduction

Several behavioral results have been interpreted as showing that reading instruction in an alphabetic script constitutes an encouragement to process speech in terms of phonemes. This holds true with regards to conceptualization of speech. Phoneme awareness develops in interaction with the acquisition of an alphabetic script (Morais, Alegria, & Content, 1987). More precisely, with the acquisition of the *alphabetic principle*, namely the intuition that graphemes (letters or groups of letters) correspond to “letter sounds”, or more exactly to phonemes (for a detailed discussion of the concept of phoneme, see Morais, 2021). Consistently, both preliterate children (e.g., Liberman, Shankweiler, Fischer, & Carter, 1974) and adults who have never learned an alphabet, either because they remained illiterate because they never attended school due to socioeconomic reasons (e.g., Morais, Bertelson, Cary, & Alegria, 1986; Morais, Cary, Alegria, & Bertelson, 1979), or because they only learned a nonalphabetic system (e.g., Read, Zhang, Nie, & Ding, 1986), are very poor at performing phonemic awareness tasks. For instance, studies that tested adult participants' ability to delete the first

phoneme of an utterance (e.g., /kat/→/at/) reported around 20% average correct responses in illiterates or nonalphabetic readers, vs. more than 70% in alphabetic literates (Morais et al., 1986, 1979; Read et al., 1986).

Notably, the representations involved in such tasks that require attention to and/or explicit manipulation of phonemes differ from perceptual representations. The same illiterate people who perform poorly on phoneme manipulation tasks discriminate almost perfectly between pairs such as /ta-sa/ or /pa-ba/ (Adrián, Alegria, & Morais, 1995; Scliar-Cabral, Morais, Nepomuceno, & Kolinsky, 1997). Yet, whether speech perceptual representations might be more finely tuned by literacy¹ acquisition remains controversial. Although several observations seem to support this idea, most of them cannot be unambiguously interpreted. For instance, illiterate adults recognize spoken words less well than literates in difficult listening conditions, namely when the task is made difficult by adding noise (Ventura, Kolinsky, Fernandes, Querido, & Morais, 2007), or with two words presented dichotically (i. e., simultaneously, one to each ear, Morais, Castro, Scliar-Cabral, Kolinsky, & Content, 1987). This literacy effect may not reflect differences

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* Corresponding author at: Unescog, Université Libre de Bruxelles, CP 191, 50 Ave. F. Roosevelt, B- 1050 Bruxelles, Belgium.

E-mail address: Kolinsky.Regine@ulb.be (R. Kolinsky).

¹ Henceforth, *literacy* will refer only to alphabetic literacy.

in perceptual processes or representations, but rather an attentional strategy based on the explicit awareness of phonemes. Whilst literate people are able to develop this strategy, illiterate people are not. This idea accounts for the fact that, in word dichotic listening, the ratio between segmental word identification errors (involving only one phoneme) and global word identification errors (involving all the segments of a syllable) was found to be lower in illiterate than in literate adults (Morais, Castro, et al., 1987). In addition, this ratio is increased in undergraduate students by instructions to pay attention to the phonemic structure of the items (Castro, 1988, 1993). Although under strategic control, this effect suggests that phoneme awareness might improve performance in word-level recognition tasks, even though this ability is not mandatory in this context.

Another way to examine whether literacy finely tunes speech perceptual representations is to use simple identification (e.g., labeling) or discrimination (e.g., same-different judgment) tasks in which stimuli differ along physical continua such as formant transitions or voice onset time (VOT, responsible for voicing). A number of studies using this approach have reported that children present an improvement of speech identification and discrimination performance that occurs maximally at the beginning of reading acquisition. This is illustrated, for instance, by studies on the developmental course of attenuation for non-native speech contrasts (cf. e.g., Werker & Tees, 1983) compared to native ones. Comparing native and non-native speech contrasts, three separate experiments on children (Burnham, 2003; Burnham, Earnshaw, & Clark, 1991) reported that for native speech contrasts, the identification function is steeper and discrimination is enhanced at the beginning of reading acquisition, these changes being significantly associated with literacy-related abilities (reading and phoneme awareness). These results were taken to support the *reading hypothesis* (e.g., Burnham, 2003), according to which “the intensification of language specific speech perception between two and six years is related to the onset of reading instruction” (Burnham, 2003, p. 576).

However, none of these studies independently manipulated age and instruction related to school experience, including reading instruction. Thus, definitive conclusions regarding the role of literacy per se cannot be drawn from those data. To overcome this limitation, Horlyck, Reid, and Burnham (2012) adopted a *cut-off design* (e.g., Cahan & Davis, 1987; Morrison, Smith, & Dow-Ehrensberger, 1995), using the relatively broad temporal window over which children start school as a means of independently manipulating age and school experience. Indeed, in some countries, children of the same age may start school up to one year apart. Horlyck et al. observed that the discrimination of a native speech contrast was not related to age, but rather to school experience and phonological awareness (as assessed by tests of syllable counting, rhyme, phoneme identification, segmentation, blending, phoneme deletion) and letter identification. These researchers speculated that the crucial element of school experience is reading acquisition. Yet, no reading test was included in that study. In addition, as acknowledged by Horlyck et al., another limitation in the implications of their results resides in a selection bias associated with the parents’ choice of school entry age.

Crucially, all those studies examined identification and discrimination performance on independent groups of participants. When considered separately, these scores reflect *categorical precision*, namely the steepness of the response change around a category boundary. The degree of nonlinearity of the response can be evaluated either by measuring the slope of the identification function around the categorical boundary (the steeper the slope of the identification function, the greater the precision, Simon & Fourcin, 1978) or by measuring the magnitude of the discrimination peak around such boundary (the larger the peak, the greater the precision, Wood, 1976).

However, categorical precision is relatively independent from *categorical perception* (for a review, see Damper & Harnad, 2000; see also discussion in Schouten, Gerrits, & van Hessen, 2003), a phenomenon in which discrimination between stimuli depends on their belonging to

distinct categories. Categorical perception is perfect when discrimination of physical differences between stimuli is entirely determined by their assignment to different categories. In this case, only differences between identified phonemic categories (e.g., between phonemes identified as /b/ vs. those identified as /d/) can be distinguished, not the within-category variants (e.g., between two physically different sounds, both identified as /b/), even if all the sounds are characterized by an equivalent acoustic difference (Liberman, Harris, Hoffman, & Griffith, 1957). This holds independently of the precision of the categorical boundary. What matters is not the sharpness of the identification or the magnitude of the discrimination peak, but how well these two measures are matched. Categorical perception is thus estimated through the relation between performance in identification and discrimination. To check for such a match, observed discrimination scores are compared to predicted discrimination scores that are derived from the identification function. The degree of categorical perception is inversely related to the size of the difference between the observed and predicted discrimination scores (Liberman et al., 1957). Categorical perception is conceived as solving the fundamental problem of mapping highly variable, continuous sensory signals onto a common category, allowing listeners to perceive stable, discrete and partially abstract categories that are relevant for meaning despite many sources of acoustic variability (e.g., Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967)².

The top part of Fig. 1 (inspired by Studdert-Kennedy, Liberman, Harris, & Cooper, 1970) presents idealized identification and discrimination functions to illustrate categorical perception, with a huge discrimination peak centered on the identification boundary. Categorical perception does not make sense without some amount of categorical precision (e.g., Schouten et al., 2003). Yet, with the exception of extreme cases where categorical precision is so weak that there is almost no discernible boundary, categorical perception and categorical precision are two distinct categorical properties. This is illustrated by the hypothetical expected and observed discrimination curves presented in the bottom part of Fig. 1 (inspired by Hoonhorst et al., 2011). This figure schematically shows how the independent variation of categorical perception and categorical precision can lead to four situations. In two cases (examples a and d), both categorical perception and categorical precision are either strong or relatively weak. The latter situation (example d) is observed in dyslexic children, who display a deficit in both categorical perception and categorical precision relative to typical readers (for a review, see Sprenger-Charolles, Colé, & Serniclaes, 2006; see also e.g., Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008). Two other cases (examples b and c) correspond to a dissociation between categorical perception and categorical precision performance. In example b, categorical precision is strong but categorical perception is relatively weak, as there is a mismatch between expected and observed discrimination scores. This situation corresponds for instance to the perception of stable vocalic segments (e.g., Fry, Abramson, Eimas, & Liberman, 1962; Pisoni, 1975; see also more recent evidence in e.g., Altmann et al., 2014). In example c, categorical perception is strong, but categorical precision is relatively weak. As we will see next, this result pattern corresponds to the one displayed by illiterate adults (Serniclaes, Ventura, Morais, & Kolinsky, 2005).

To our knowledge, only two studies to date have examined the impact of literacy acquisition on both categorical precision and categorical perception. One included adults and children from the last year

² Yet it is now acknowledged that sensitivity to subphonemic details also helps word recognition, for instance, through the necessary interpretation of anticipatory coarticulatory information (e.g., Mahr, Saffran, Weismer, & Edwards, 2015). Also, that categorical perception is almost never “perfect” (i.e., with no difference at all between predicted discrimination and actually measured discrimination). Several models suggest that listeners have simultaneous access to both continuous acoustic cues and discrete categories (e.g., Pisoni & Tash, 1974).

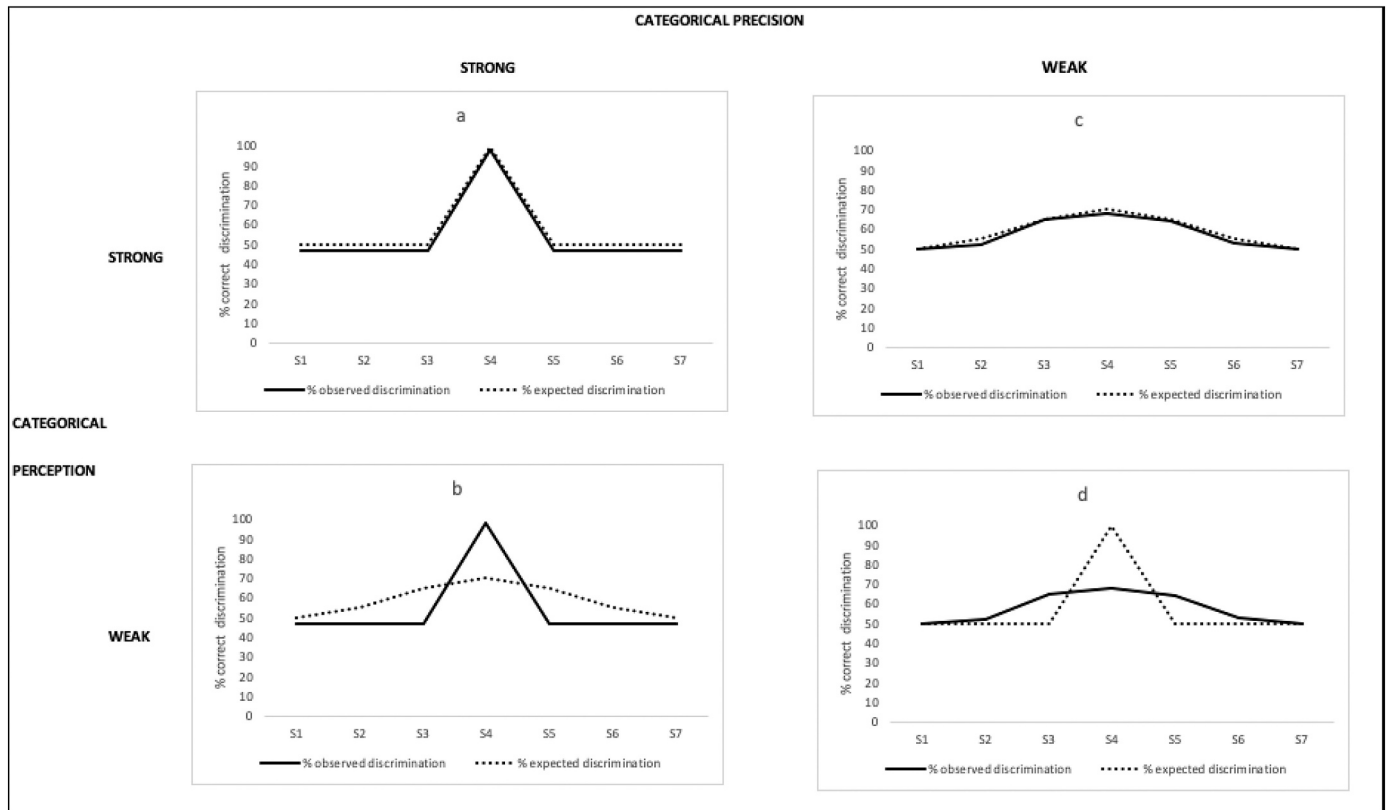
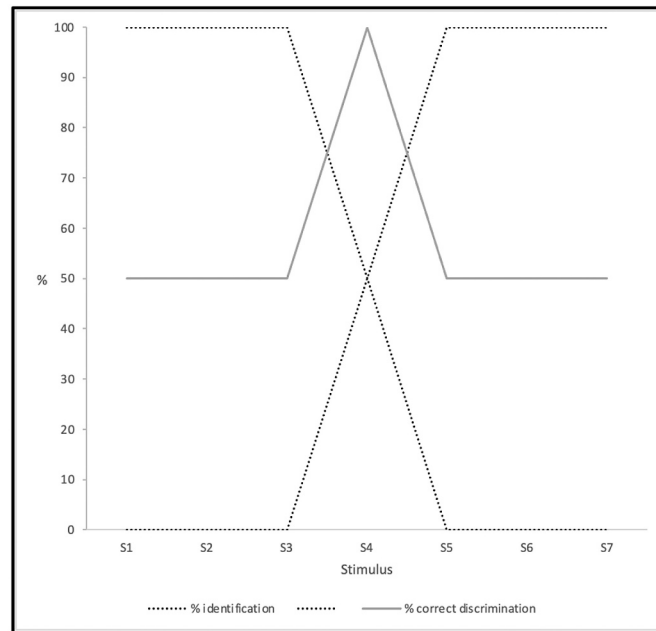


Fig. 1. Top: idealized identification (dotted black line) and discrimination (plain gray line) functions to illustrate categorical perception of seven stimuli distributed at equal intervals along a physical continuum. Bottom: Hypothetical expected and observed discrimination curves. Categorical precision is larger when the discrimination peak is higher, and categorical perception is greater when the observed and expected peaks are matched.

of kindergarten to the second grade of primary school, and used a voicing continuum (Hoonhorst et al., 2011). The other compared adults of different literacy levels and used a place-of-articulation continuum (Serniclaes et al., 2005). In both studies, there was a significant relationship between literacy (and correlated schooling level) and categorical precision, whereas categorical perception was found to be similar whatever the level of literacy/schooling. These two sets of data thus

suggest that instruction (either specifically literacy, and/or schooling) helps to fine tune phonemic boundaries, therefore increasing the precision of phoneme identification, but does not change categorical perception per se. Thus, both studies indicate that categorical precision and categorical perception are dissociable, with only the former being modulated by instruction. The same held true for the effect of age: whilst categorical perception did not change across age, categorical precision

improved between kindergarten and adulthood (Hoonhorst et al., 2011; see also similar results in Medina, Hoonhorst, Bogliotti, & Serniclaes, 2010; Medina & Serniclaes, 2009).

Nonetheless, the study on children was unable to dissociate the effect of literacy from the effect of age (Hoonhorst et al., 2011). The study on adults (Serniclaes et al., 2005) was also limited, because correlations between literacy level and categorical precision or perception could not be examined, as the two participant groups represented two extreme ends of the literacy spectrum, namely, fully illiterate unschooled adults and schooled literate adults.

In addition, Serniclaes et al. (2005) acknowledged that their adult data could be attributed to a lexical bias, as one of the end points of the /ba-da/ speech continuum that they used was a word. Indeed, in addition to displaying a shallower slope of the labeling function than literates, illiterate adults differed from literates in the intercept of the labeling function. This intercept difference reflected a bias towards /da/ responding in the illiterate group, which may have been due to a lexical bias: whereas in Portuguese (the language of the study) /ba/ is nonsense, /da/ is an extremely frequent form of the verb “dar”, which means “give”. A lexical bias has repeatedly been documented in the illiterate population. For instance, in pseudoword immediate repetition, lexicalization errors (i.e., word responses to phonologically related pseudowords) were fewer than 2% of the errors in the literate adults examined by Castro-Caldas, Petersson, Reis, Stone-Elander, and Ingvar (1998) but reached 11% in the illiterate group. The strong bias for identifying the first stimuli of the continuum as /da/ instead of /ba/ in illiterate adults is likely to be a further instance of this lexical bias and may have affected categorical precision. In agreement with this idea, Serniclaes et al. found the intercept of the labeling function to be highly correlated to the slope of this function³. Thus, it remains unknown whether illiterate adults actually differ from literates in categorical precision, or whether this effect was only related to the lexical bias induced by the material used by Serniclaes et al.

A further concern relates to the nature of the stimuli in both the adult study (Serniclaes et al., 2005) and the developmental study (Hoonhorst et al., 2011). In the latter study, responses were collected with a VOT continuum with two lexical endpoints (the French words “de” and “te”), excluding an explanation in terms of lexical bias. However, the effect of reading experience on categorical precision was probably due to another stimulus factor. Although VOT is the primary acoustic cue to voicing, the perception of voicing (and other phonological features) depends on the integration of multiple acoustic cues (burst loudness: Repp, 1979; first formant characteristics: Summerfield, 1982; formant transitions: Stevens & Klatt, 1974; fundamental frequency – F0 – characteristics: Haggard, Summerfield, & Roberts, 1981). In many studies using a synthesized voicing continuum, including Hoonhorst et al.’s, only the primary acoustic cue to voicing (i.e., VOT) was modified. Most of the secondary cues to voicing did not covary with VOT in the stimuli, giving rise to conflicting phonological information at the continua endpoints. When the cue stimuli were conflicting, kindergarteners were unable to fully recognize the phonological categories. Hoonhorst et al. reported that this deficit diminished with age, as reading acquisition developed. Similarly, in Serniclaes et al. (2005) only the primary acoustic cues to place of articulation (the second and third formant transitions, F2 and F3, respectively) were modified. The use of stimuli with conflicting acoustic cues, namely of extra-prototypical stimuli, was thus probably at the origin of an effect of reading experience on categorical precision in both studies, in addition to the lexical bias that Serniclaes et al. reported. In agreement with this view, both effects concerned the identification responses at the continua endpoints (the asymptotes of the response function), not those around the boundary. These effects correspond to a

³ However, and in agreement with the assumption of independence between categorical perception and precision, the intercept was uncorrelated to the degree of categorical perception.

generalization of the categorical representations, for either non-words (Serniclaes et al.) or extra-prototypical stimuli (both Hoonhorst et al. and Serniclaes et al.), rather than to actual improvements in the precision of the boundary between categories. The question that remains is whether literacy has a genuine effect on boundary precision, irrespective of the generalization effects that were shown in previous studies.

The aim of the present study was to reevaluate the impact of literacy on categorical precision and categorical perception by examining its impact independently of the effect of age, and by using more controlled stimuli, without lexical bias and without conflicts between acoustic cues. In line with Hoonhorst et al. (2011), we used a voicing continuum⁴, presenting participants with both an identification (labelling) and a discrimination (same/different) task. In order to avoid lexical biases, we selected words of similar frequency that were letter names (/de/ –/te/), as continua endpoints. This continuum was generated by morphing (interpolation) between natural speech exemplars pronounced by a native (Brazilian) male speaker. We chose this procedure to minimize possible differences in categorical precision arising from a lack of perceptual integration between the different acoustic cues that contribute to the perception of the same feature. With morphing, possible conflicts between these different acoustic cues are minimized because all the relevant acoustic cues for a given feature are modified simultaneously. Thus, in the present study, the use of stimuli generated by morphing allowed the possible effects of reading on boundary precision to be examined.

We examined the categorical perception of speech sounds and the precision of phonemic categories in groups of adult and children beginning readers, as well as in more fluent adult readers. Beginning readers were 7- to 8-year-old children attending Grade 2, or adults who had not attended school in childhood (or only for a short time) but were attending adult literacy classes at the time of testing (henceforth, *unschooled adults*). Fluent readers were adult participants that had attended school and hence had learned to read and write in childhood (henceforth, *schooled adults*). We carefully evaluated the literacy level of all the participants. As all adult participants were of modest socioeconomic status (SES) and as the literate schooled adults had only attended (usually low-quality) school for up to five years, we expected variability in literacy level across all groups.

Unschooled adults presented a word reading fluency level similar to the one of the Grade 2 children (details are presented in Results section). Hence, assuming that the results from the former studies were not due to a lexical bias (Serniclaes et al., 2005), to the use of conflicting-cue stimuli (Hoonhorst et al., 2011; Serniclaes et al., 2005), or to age differences (Hoonhorst et al., 2011) but reflect a genuine effect of literacy on categorical precision, we expected to observe a categorical precision difference (but no categorical perception difference) between schooled adults and unschooled adults, but no significant difference between the latter and Grade 2 children. We thus predicted that schooled and unschooled adults would differ in terms of the slope of the identification function and/or size of the discrimination peak around the phoneme boundary. In contrast, no group differences were expected in terms of the relation between performance in identification and discrimination (i.e., in terms of categorical perception). We further expected the categorical precision indexes (slope of the identification function and/or size of the discrimination peak) to be correlated with participants’ literacy level, not their age. No significant correlation (neither with age, nor with literacy) was expected with categorical perception.

⁴ We initially tried to use also a place-of-articulation continuum. Yet, unexpectedly, this led to very poor discrimination scores in the schooled adults and was therefore inappropriate for group comparison purposes.

2. Method

2.1. Participants

All participants were fully functional in their daily lives and socially integrated. They volunteered and gave their informed consent, as did the children's parents. Only Brazilian Portuguese natives with no hearing impairment and with no cognitive, speech or language disorder were included in the study. To this aim, all participants were screened for auditory difficulties and they (or their parents) were asked about their native language and possible speech or language disorders. Adults were also screened for cognitive impairments.

The auditory screening consisted of acoustic immittance tests with broadband stimulus, search of acoustic reflex thresholds and capture of distortion product otoacoustic emissions, using the TITAN - Inter-acoustic Equipment (IMP440 Module - Broadband Immittance / Tympanometry Module - and DPOAE440 Module - Distortion Product Otoacoustic Emissions Module).

From an initial sample of 57 adults, five presented hearing impairments, three were not Brazilian Portuguese natives, two were of an age that was outside the other participants' age range (see below; one was 16 years old, the other 67 years old) and two correctly identified only one of the endpoints of the speech continuum. These adults were all excluded, leaving a sample of 45 (29 unschooled vs. 16 schooled adults). None of them had a cognitive impairment, as evidenced by their scores on the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975; for the Portuguese version: Guerreiro et al., 1994). With average scores of 26.88 in schooled adults (SD = 1.67) and 23.24 in unschooled adults (SD = 3.5), these were within the normal range for adults with a low formal education level (Caramelli, Herrera, & Nitri, 1999)⁵.

The adults of the final sample were all of relatively modest SES, according to the Brazilian Criterium of Economic Classification (Critério de Classificação Econômica Brasil – CCEB, Associação Brasileira de Empresas de Pesquisa, 2015; <http://www.abep.org/criterio-brasil>). This classifies the population based on the ownership of assets with a score for all possessions, as estimated through a questionnaire about home facilities and transportation (e.g., number of bathrooms, of domestic servants, of refrigerators, of cars, etc.), formal education, and access to public utility services (e.g., paved street or not). Each SES class is defined by the sum of those scores. There was only a marginal difference in SES between the two adult groups, Mann-Whitney *U* test = 315, *p* = .05; effect size (rank biserial correlation) = 0.36, with slightly higher average SES scores in schooled adults (26.87, SD = 6.93) than in unschooled ones (22.86, SD = 6.41). Participants differed more strongly on age, with unschooled participants being older than schooled ones (on the average, 48.38 years, SD = 8.07 vs. 39.75 years, SD = 7.13, respectively), *t*(43) = 3.573, *p* < .001, *d* = 1.113.

From an initial sample of 57 Grade 2 children, five presenting serious speech or language disorders were excluded. The remaining 52 Grade 2 children were aged 7.94 years, on the average (SD = 0.37; range: 7.25–8.75 years).

Reading was assessed in all selected participants through three tests. One included 36 words (12 simple, 12 complex and 12 irregular ones). Another included 16 pseudowords (8 simple and 8 complex ones). Both were adapted from Morais et al. (2010). Reading fluency was assessed by presenting participants with a list of 108 upper-case words that increased in level of difficulty (according to length, complexity, and regularity), and requiring them to read as many words as they could in one minute (Vidigal de Paula & da Silva Leme, 2017); number of correct words per minute (WPM) was analyzed.

In addition, selected participants were presented with a test of letter knowledge (oral identification of 23 upper-case letters) as well as with

three metaphonological tests of varying difficulty, adapted from Morais et al. (2010): phonological sensitivity, initial syllable deletion, and the more difficult test of initial phoneme deletion (e.g., Liberman et al., 1974).

In the phonological sensitivity test, participants were presented with six panels, each with six drawings of common objects. On each panel, they were asked to point to the drawings corresponding to names of objects that started with a target phoneme. In the demo trial, for the phoneme /f/, they heard six real words uttered by the experimenter: “fita”, “fada”, “ferro”, “fumo”, “fato”. Their attention was directed to the fact that all words started with the /f/ “sound”. They were next presented with six drawings and asked to point to those corresponding to a name starting with /f/. On each panel there were between two and four target images (total: 18), half with a name starting with a simple (C) onset (e.g., “faca”), the others with a name starting with a complex (CC) onset (e.g., “flor”, “frasco”). The foil words had quite different onsets compared to those of the targets (e.g., “escada”, “osso”, “índio”).

In both deletion tests, participants had to repeat part of a spoken pseudoword uttered by the experimenter after having deleted its initial part, either the first syllable (e.g., /kɔbu/ → /bu/) or the first phoneme (e.g., /tɔbu/ → /ɔbu/). All expected responses were also pseudowords. Each deletion test included 10 disyllabic items (all CVCV in the phoneme deletion test), plus two training trials with corrective feedback.

Two tests of rapid automatized naming (RAN) were also presented, one on pictures (of a boat, key, chair, pencil, fish and star) and one on digits (from 2 to 8). Participants were instructed to name the items, repeated in random order for a total of 36 stimuli. The time in seconds that they took to name the 36 stimuli was recorded. Previous studies have reported that such a measure of phonological processing is related to reading abilities (e.g., Araújo, Fernandes, & Huettig, 2019) in a way that is independent from other abilities such as phonological awareness (e.g., Powell, Stainthorpe, Stuart, Garwood, & Quinlan, 2007; for a metanalysis, see Araújo, Reis, Petersson, & Faisca, 2015).

Average performance of the final samples on all the ancillary tests are presented in Table 1.

2.2. Materials

A six-steps voicing continuum, /de/–/te/ (henceforth, S1–S6) was presented. High-quality speech stimuli were synthesized using TANDEM-STRAIGHT (Kawahara et al., 2009; Kawahara & Morise, 2011), a MATLAB tool that provides a temporally stable power spectral representation of the initial (prototypical) two syllables (i.e., /de/ and /te/). On the basis of the spectrographic representations of these two periodic signals, we implemented a morphing algorithm (Kawahara & Matsui, 2003) that first consisted of manually assigning anchor points. We located 20 anchors that were regularly spaced and similarly placed on each prototypical syllable. The morphing algorithm then followed a four-stage procedure, which consisted of: (i) aligning the time frequency coordinates of the two prototypical syllables, (ii) interpolating parameters represented on the aligned time-frequency coordinates according to the given morphing rate (i.e., a six step-rate), (iii) deforming the time-frequency coordinates according to the given morphing rate, and (iv) resynthesizing six sounds using the morphed parameters in the morphed time-frequency coordinates. The morphing procedure was applied to all parameters (F0, periodicity and spectrogram).

Each stimulus was presented 10 times in the identification test, in pseudo-random order, leading to a total of 60 identification trials. For the discrimination test, 10 “different” pairs of stimuli were created, each stimulus being paired with the adjacent one on the continuum (e.g., S1–S2; S2–S1; S2–S3, etc.). There were also six “same” pairs in which each stimulus was paired with itself. Each of these 16 pairs was presented five times, in random order, leading to a total of 80 discrimination trials.

2.3. Procedure

The study was approved by Santa Casa Medical Sciences ethics

⁵ Almost half of the unschooled adults (48.28%) were unable to answer the two items that required reading or writing.

Table 1
Average values on the ancillary tests. Standard deviations in brackets. Scores in bold were those used in the correlation analyses.

Group	Letter			Reading			Reading fluency			Phonological awareness				RAN		
	Mean	SD	Range	Words	Pseudowords	Average	Syllable deletion	Phoneme deletion	% correct	Phonological sensitivity	Average	Pictures	Digits	Average		
Unschooling adults	97.0	[4.66]	86.61–100	83.46 ^a	70.31 ^b	76.06^b	57.24	11.72	54.6	41.19	35.87	27.57	31.72			
	Mean	SD	Range	[16.41]	[19.01]	[16.18]	[40.7]	[25.08]	[34.19]	[26.7]	[5.1]	[5.48]	[4.67]			
Schooling adults	99.19	[2.37]	98.44–100	98.44	92.97	95.7	95.00	84.38	68.75	82.71	29.15	18.24	23.7			
	Mean	SD	Range	[2.48]	[6.81]	[3.99]	[15.06]	[19.99]	[18.13]	[14.04]	[7.91]	[2.54]	[4.62]			
Grade 2 children	91.67	[23.85]	56.76–100	56.76	54.96	55.86	40–100	20–100	33.33–100	53.33–100	18–48.7	13.5–23.28	15.75–33.8			
	Mean	SD	Range	[35.45]	[35.31]	[34.88]	[16.46]	[4.65]	[34.63]	[23.08]	[17.17]	[15.05]	[13.95]			
Unschooling vs. schooled adults ^c	292.5 ^(*)	0.26	0–100	0–97.44	0–100	0–96	0–100	0–100	0–100	0–100	29–110	20–112	26–90			
	Effect size ^d	0.26	Range	303.5 ^(*)	293.5 ^(*)	454.5 ^(*)	372.5 ^(*)	445.5 ^(*)	288	0	99 ^(*)	17 ^(*)	17 ^(*)			
Unschooling adults vs. Grade 2 children ^c	794	0.26	0–100	0.72	0.83	0–96	0.61	0.92	0.24	0	–0.57	–0.93	–0.93			
	Effect size ^d	0.05	Range	304 ^(*)	420.5	822	1014.5 ^(*)	1177.5 ^(*)	545 ^(*)	–0.28	0.77	0.52	0.52			

(*) $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .005$, **** $p < .001$.

^a only 22 participants out of 29 agreed to participate in this test.

^b only 20 participants out of 29 agreed to participate in this test.

^c Mann-Whitney tests.

^d rank biserial correlation.

committee (protocol no. 64381417.5.0000.5479). Participants were first presented with the questionnaires on schooling history, SES level, MMSE, and the auditory screening. Then they were presented with the phonological processing tasks, namely the metaphonological (phonological sensitivity, phoneme and syllable deletion) and RAN (pictures and digits) tests. On a second session participants were presented with the speech identification and discrimination tests, as well as the reading tasks (letter, word and pseudoword recognition, and reading fluency). As the same participants were presented with another (place of articulation) continuum as well (see footnote 4), order of the materials was counterbalanced across participants.

For the speech identification and discrimination tests, stimuli were presented through headphones at 40 dB, using the PRAAT software (Boersma, 2001; Boersma & Weenink, 2019) running on a Macbook Air 13" computer. Participants first performed the identification test, then the discrimination test. As some participants were almost illiterate, the experimenter asked them to respond orally in both tests and entered the response herself into the computer by pressing the corresponding response (keyboard) keys.

In the identification test, one syllable was presented on each trial. Participants were told that they would hear either /de/ or /te/ and were instructed to report which of the two sounds they heard. In the discrimination test, syllables were presented in pairs with a 300 ms between-syllables interval. Participants had to say whether the stimuli within each pair were the same (either two /de/, or two /te/ syllables) or different (/de/-/te/ or /te/-/de/).

2.4. Data analysis

Data are available on the Open Science Framework at <https://osf.io/4fmzy/> (Kolinsky, 2020). All the analyses were performed using JASP 0.13.1 (JASP Team, 2020). Performance on the ancillary tests were analyzed through Mann-Whitney tests. For the speech perception tests, for each participant, identification scores were calculated as the mean of /de/ responses collected for each stimulus. Correct discrimination scores were calculated for each participant and for each pair (e.g., S1S2). In order to assess categorical perception following the classical procedure (Liberman et al., 1957), observed discrimination scores were compared to predicted discrimination scores that were derived from the identification scores using the following probability formula (adapted from Pollack & Pisoni, 1971): $P(\text{correct response}/S1, S2) = \text{mean of predicted correct response to different and same pairs} = [P(R/S1) * (1 - P(R/S2)) + (1 - P(R/S1) * P(R/S2))]/2 + [P(R/S1) * P(R/S1) + (1 - P(R/S1) * (1 - P(R/S1) + P(R/S2) * P(R/S2)) + (1 - P(R/S2) * (1 - P(R/S2)))]/4$, where R is one of the two possible identification responses (“de” or “te”).

The discrimination responses were then converted into d' values by taking the difference between the normal deviate (z -score) corresponding to the proportion of hits (correct difference detections i.e., proportion of “different” responses to different pairs) and the proportion of false alarms (i.e., proportion of “different” responses to same pairs). Since 0% and 100% scores correspond to infinite z scores, response scores were adjusted following the classical procedure described by Macmillan and Creelman (2005), with proportions of 0 and 1 adjusted to $[1/(2N)]$ and $[1-1/(2N)]$, respectively, where N is the number of trials on which the proportion is based.

The d' values were then entered into an omnibus ANOVA with Pair (5 values: S1S2 to S5S6), Task (identification, discrimination) and Group as factors⁶. A group difference in categorical precision would lead to a significant Pair X Group interaction and a group difference in categorical perception to a significant Pair X Task X Group interaction.

⁶ As we initially used two continua on the adult participants, namely a place-of-articulation continuum in addition to the voicing one, first we had checked that order of presentation of the materials did not interact with these variables of interest.

For the computation of correlations, several indexes were calculated for each participant. Categorical precision was estimated by means of the *discrimination peak* and the slope of the identification function, calculated separately for each participant. The discrimination peak was taken as the difference between the largest d' score (averaged over observed and expected data), irrespective of the location of the phoneme boundary, and the mean of the other d' scores (also averaged over observed and expected data). Categorical perception was estimated by means of a *categorical perception index*, which reflects the difference between observed and expected discrimination performance. Indeed, this index was obtained by taking the absolute difference between the expected and observed discrimination peaks, after having individually adjusted those scores for the location of the boundary.

Regarding literacy, we considered five scores in the computation of correlations: correct performance on letter knowledge, average word and pseudoword reading, average phonological awareness (three tests), word reading fluency, and average RAN performance. All the correlations were Bonferroni-corrected, and, with one exception, were examined through one-sided tests, as the alternative hypotheses were that literacy and/or age would improve categorical precision or perception. Yet we used a two-sided test to examine the correlation between categorical perception and age because, to our knowledge, an effect of age on categorical perception has been reported only once (Elliott, Longinotti, Meyer, Raz, & Zucker, 1981), with a negative effect indicating an age-dependent decrease in the categorical perception of place-of-articulation. Other studies examining a voicing contrast reported a nonsignificant correlation with age (e.g., Hoonhorst et al., 2011; Medina et al., 2010), and no significant change between four and ten years of age (Medina & Serniclaes, 2009).

3. Results

First, performance of the two groups of adults was compared in order to examine the impact of literacy and instruction. Next, performance of the group of uneducated adults was compared to the Grade 2 children in order to examine the impact of age in those participants matched on reading fluency. Finally, correlations were computed across the three groups.

3.1. The impact of literacy and instruction: comparison between schooled and uneducated adults

3.1.1. Ancillary tests

As can be seen in Table 1, uneducated adults presented significantly lower scores than schooled adults in all tests, except on phonological sensitivity and letter knowledge⁷.

3.1.2. Categorical perception and precision

The labeling functions, as a function of stimulus, are presented in Fig. 2, separately for each group; discrimination performance, as a function of pair, is displayed in Fig. 3, separately for each group.

The Pair X Task X Group (uneducated vs. schooled adults) repeated measure ANOVA conducted on d' showed significant main effects of Pair, $F(1.286, 172) = 304.907, p < .001, \eta^2_p = 0.876$, with S3S4 leading to the best performance compared to all other pairs, all $t(43) > 27$, all $ps < 0.001$ ($ps = 1$ for all other comparisons). There was also a significant main effect of Group, $F(1, 43) = 10.656, p < .005, \eta^2_p = 0.199$, with uneducated adults displaying overall lower performance than schooled adults. In addition, there was a significant Pair X Group interaction, $F(1.286, 55.293) = 9.969, p < .001, \eta^2_p = 0.188$, which reflects the fact that groups differed significantly only on the S3S4 pair, $F(2, 172) =$

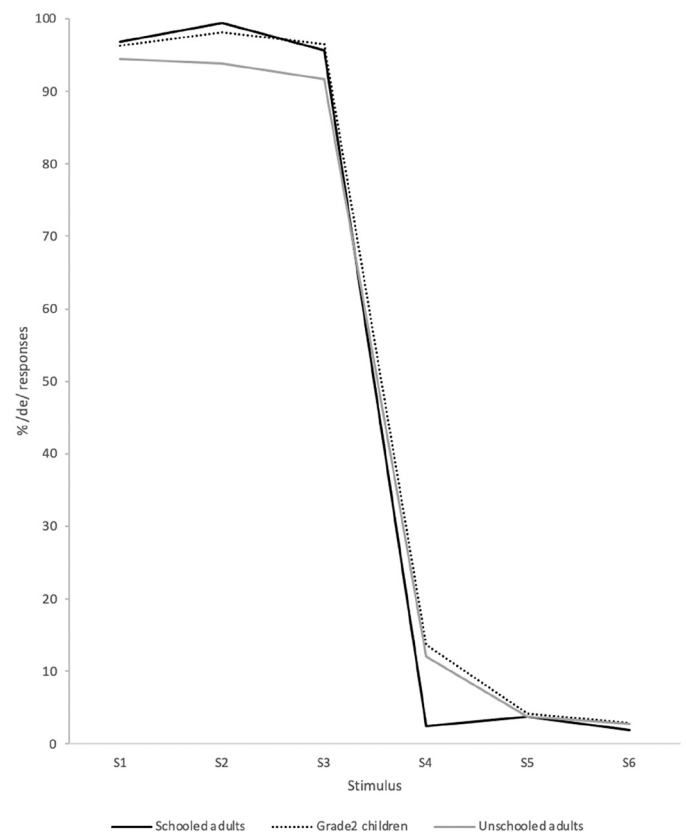


Fig. 2. Labeling functions (% of /de/ responses) of each group. Uneducated adults: plain gray line; schooled adults: plain black line; Grade 2 children: dotted black line.

11.829, $p < .001$ (all other $ps \geq 0.10$, except on S2S3, $F(2, 172) = 3.234, p = .08$). However, the Pair X Task X Group interaction was not significant, $F(1.369, 58.847) = 1.129, p = .31, \eta^2_p = 0.026$. Results were similar with age as covariate, with a significant Pair X Group interaction, $F(1.282, 53.832) = 6.944, p < .01, \eta^2_p = 0.142$ and a nonsignificant Pair X Task X Group interaction, $F(1.366, 57.392) = 1.505, p = .231, \eta^2_p = 0.035$.

A similar Bayesian repeated measures ANOVA supported the idea that there is evidence in favor of a group difference in categorical precision, with a Bayesian factor $BF_{incl} = 6723E+05$ for the Pair X Group interaction, as well as in favor of no group difference in categorical perception, with a Bayesian factor $BF_{excl} = 6.326$ for the Pair X Task X Group interaction. In other words, the data are about 672 thousand times more likely to be in line with the hypothesis that there is a group difference in categorical precision, than in line with the null hypothesis (H_0). This is considered to be very strong (Raftery, 1995) or decisive (Jeffreys, 1961) evidence for the alternative hypothesis (H_1) over H_0 . Data are also about six times more likely to be in line with the hypothesis that the groups do not differ on categorical perception than under H_1 , which is considered as positive (Raftery, 1995) or substantial (Jeffreys, 1961) evidence for H_0 over H_1 .

3.2. The impact of age: comparison between reading-matched grade 2 children and uneducated adults

3.2.1. Ancillary tests

We first checked whether the reading level of the children and adult participants was equivalent. We could not rely on their performance on word and pseudoword reading, due to the relatively large proportion of the uneducated adults who declined to participate in these tests (24% and 31%, respectively, see Table 1). Therefore, word reading fluency

⁷ The uneducated adults' performance on word and pseudoword reading that is presented in Table 1 is inflated by the fact that many did not agree to take part in these tests (see Table 1).

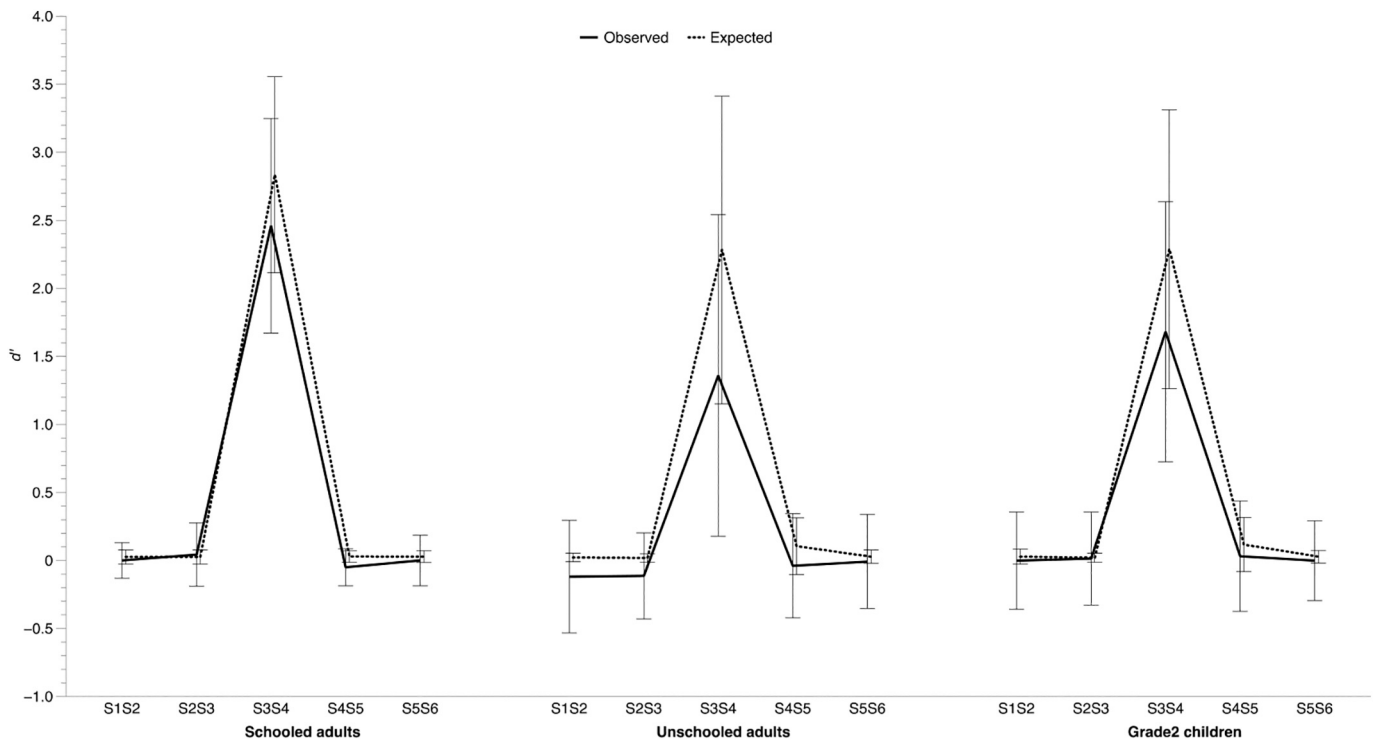


Fig. 3. Average discrimination scores (d') in each group, for observed performance (plain lines) and performance predicted on the basis of identification (dotted lines). Error bars represent standard deviation of the mean.

was examined, which had been evaluated on all participants. On this test, no significant difference was observed (Table 1). As also shown in Table 1, schooled literates struggled on phoneme (and even syllable) deletion, presenting poorer performance than the children, which is a common observation in adults with low levels of literacy (e.g., Eme, Lambert, & Alamargot, 2014; Greenberg, Ehri, & Perin, 1997; Thompkins & Binder, 2003).

3.2.2. Categorical perception and precision

The children's mean identification (labeling) function are presented in Fig. 2, and detailed discrimination performance, as a function of pair, is displayed in Fig. 3.

The repeated measure ANOVA on the d' response scores, with Pair, Task and Group (Grade 2 children vs. unschooled adults) as factors, showed a significant main effect of Pair, $F(1.27, 100.12) = 315.219$, $p < .001$, $\eta^2_p = 0.80$, with S3S4 leading to the best performance compared to all other pairs, all $t(79) > 27$, all $ps < 0.001$ ($ps = 1$ for all other comparisons). The Pair X Group and Pair X Task X Group interactions were both non-significant, both $Fs < 1$. A similar Bayesian repeated measures ANOVA supported the idea that there is strong (Raftery, 1995) or very strong (Jeffreys, 1961) evidence in favor of the hypothesis that groups do not differ from each other, neither in categorical precision, with $BF_{\text{excl}} = 72.197$ for the Pair X Group interaction, nor in categorical perception, with $BF_{\text{excl}} = 33.685$ for the Pair X Task X Group interaction.

3.3. Correlations across the three groups

Appendix A presents the average values of the speech perception indexes used in the computation of correlations and Appendix B presents the correlation coefficients values between these indexes and performance on ancillary tests, as well as their significance levels. Across the three groups, no significant correlation was observed between the literacy scores and the slope of the identification function, probably due to a ceiling effect on this parameter (see Fig. 2). Yet there were significant correlations between all the literacy scores and the discrimination peak

(see Fig. 4 for two illustrations). In contrast, no correlation between the literacy scores and the categorical perception index reached significance. Although there was a non-significant trend for the correlation with reading fluency ($p = .07$), the more robust Bayesian correlation tests were inconclusive, supporting neither H_0 ($BF_{0-} = 0.267$) nor H_1 ($BF_{-0} = 3.747$; cf. Goss-Sampson, van Doorn, & Wagenmakers, 2020). Age did not correlate with any of the speech perception indexes. Yet, with the exception of slope ($BF_{0+} = 7.65$), the Bayesian correlation tests seeking evidence for H_0 (no correlation) were inconclusive, with $BF_{0+} = 3.209$ for the discrimination peak and $BF_{01} = 3.885$ for categorical perception.

4. Discussion

The aim of the present study was to reevaluate the impact of literacy on categorical precision and categorical perception by disentangling the effects of literacy and of age, and by using more controlled stimuli than in previous studies. Only two previous studies have examined this issue, and both reported a literacy effect on categorical precision, but no effect on categorical perception. One of the studies involved adults of varying literacy levels and used a place-of-articulation continuum (Serniclaes et al., 2005), the other involved children and adults and used a voicing continuum (Hoonhorst et al., 2011). The study on children further reported that age modulated categorical precision, but not categorical perception (see also Medina et al., 2010; Medina & Serniclaes, 2009).

Yet, the study on children could not dissociate the effects of literacy from those of age. The study on adults was also limited, because correlations with literacy level could not be examined, as fully illiterate unschooled adults were contrasted with schooled literate adults, meaning there was relatively little variation in literacy competence. In addition, these previous studies used synthesized stimuli in which only the primary acoustic cues to either place of articulation (F2 and F3 transitions, Serniclaes et al., 2005) or voicing (VOT, Hoonhorst et al., 2011) were modified, a procedure that produces conflict with secondary cues that remain unmodified. This conflict may itself hinder the

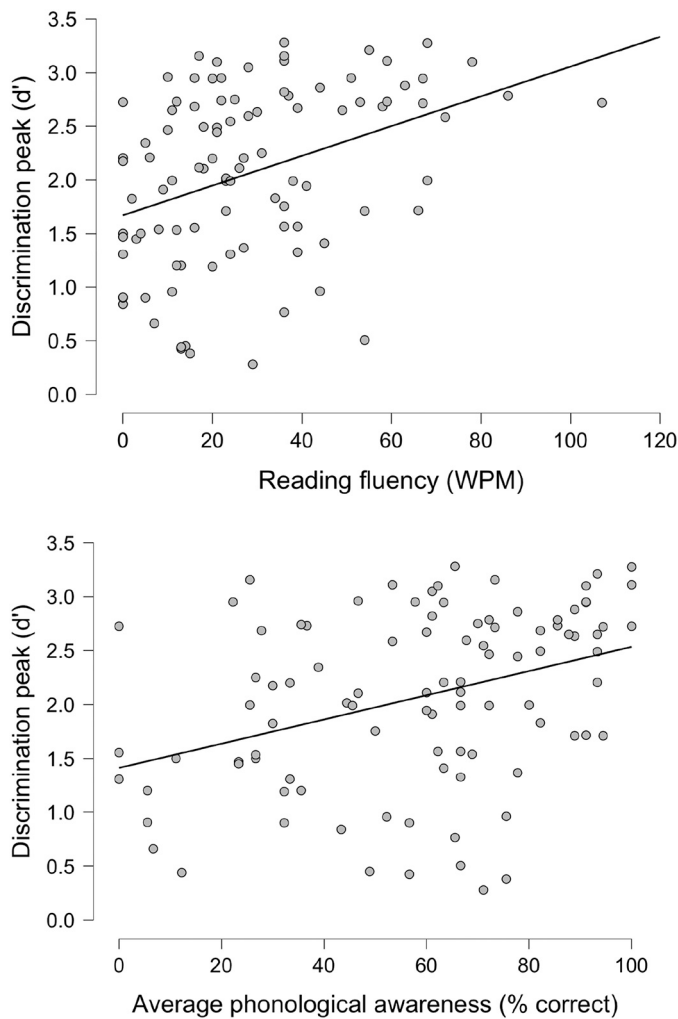


Fig. 4. Correlations observed on all the participants between the discrimination peak and either reading fluency (top) or average phonological awareness (bottom).

precision of the categorical prototypes inside each category. In these studies, the use of stimuli with conflicting acoustic cues was thus probably at the origin of an effect of literacy on the precision of the categorical prototypes rather than on the precision of the boundary. Furthermore, in the adult study, the authors reported a lexical bias that may have affected the results.

In the present study, we used a voicing continuum (as did Hoonhorst et al., 2011) without lexical bias and without conflict between acoustic cues, which was generated by morphing between natural speech exemplars pronounced by a native speaker. First, we compared participants that were matched on age but varied on literacy levels (schooled and unschooled adults). Second, we compared participants that were matched on literacy level but varied in age (children and unschooled adults). The latter had not (or almost not) attended school in childhood but were attending adult literacy classes at the time of testing and were thus also beginning readers. All the participants' literacy level was carefully evaluated.

The two adult groups did not differ significantly from each other in categorical perception, and Bayesian analyses even showed substantial evidence supporting the hypothesis that there was no group difference. In contrast, the two adult groups differed strongly on categorical precision, suggesting that literacy impacts on categorical precision even when age is held constant. The comparison of the unschooled adults to reading-matched Grade 2 children further demonstrated that the effect

of literacy is independent from the effect of age. Indeed, no significant group difference was observed in either categorical precision or categorical perception. Moreover, Bayesian analyses provided strong evidence in favor of the hypothesis that there is no group difference in categorical precision or categorical perception. Thus, when matched on reading level, adults and children performed similarly.

The analysis of correlations across the three groups showed no significant association between the literacy scores and the categorical perception index. In contrast, there were significant correlations between the discrimination peak (reflecting categorical precision) and all the literacy scores.

In addition, age did not correlate with any of the speech perception scores. This absence of correlation, combined with the nonsignificant comparison between the unschooled adults and 7- to 8-year-old reading-matched children, suggests that age does not impact speech perception in terms of either categorical precision or categorical perception, at least for the age range considered in the present study.

Note that due to the difficulty of assessing identification in infancy, categorical perception data are available only for older children (e.g., kindergarteners), and that even in this later age range most previous studies did not collect the necessary data to investigate a possible effect of age on categorical perception. An effect of age on categorical perception was reported only once (Elliott et al., 1981), with a negative effect indicating an age-dependent decrease in the categorical perception of place-of-articulation. Several other studies using a voicing continuum in French reported a nonsignificant correlation with age (e.g., Hoonhorst et al., 2011; Medina et al., 2010), with no significant change between four and ten years of age (Medina & Serniclaes, 2009), and even between kindergarteners and adults (Hoonhorst et al., 2011).

In contrast, several studies reported that categorical precision increases with age (e.g., Hoonhorst et al., 2011; Medina et al., 2010; Simon & Fourcin, 1978; for a review, see Table 1 in Hoonhorst et al., 2011). However, with regards to the perception of voicing in French specifically, significant age differences in categorical precision were observed only between kindergarten and adults, with no difference being observed between second graders and adults (Hoonhorst et al., 2011). Medina et al. (2010) also reported an effect of age on categorical precision, with steeper identification slopes in adults and adolescents (17-year-olds) than in 9-year-old children. Yet, this effect was mainly due to floor and ceiling effects affecting the endpoints of the identification functions rather than the boundary region.

In summary, the present study shows an effect of literacy on categorical precision that is independent of age, a result which is compatible with those of several previous studies. However, a genuine effect of age does remain possible, and is probably at the origin of early developments of perceptual precision such as those observed by Simon and Fourcin (1978) on 4-year-old children. Further work is thus needed to better understand to what extent, and at what point in development, age modulates categorical precision. Also, the impact may vary according to type of stimulus (e.g., the synthetic stimuli used in former studies vs. the more natural, nonconflicting stimuli used in the present study).

The second key finding of the present study was to confirm the absence of an effect of literacy on categorical perception, despite its impact on categorical precision. These results are not surprising if we consider the previous evidence indicating a dissociation between these two categorical properties. A deficit in categorical precision is commonly found in the context of developmental disorder, not only in dyslexia (Noordenbos & Serniclaes, 2015) but also in people with a hearing deficiency (Bouton, Serniclaes, Colé, & Bertoncini, 2012) and in autistic spectrum (You, Serniclaes, Rider, & Chabane, 2016). Categorical precision is associated with various factors, either sensory or phonological in nature, and variations in any of these factors, whatever their nature, affect the precision of the phonological categories. However, while these factors induce fairly large changes in categorical precision, they do not necessarily affect categorical perception. For instance, Medina and Serniclaes (2009) examined the development of different

groups of normal-hearing children, between four and ten years of age, and of deaf children with cochlear implants. Similar results were obtained for the normal-hearing children and for the cochlear-implant children with the same amount of perceptual experience (i.e., with the same auditory age, namely the length of implant usage in deaf children). These results demonstrated that categorical precision increased with age whereas categorical perception did not change.

The fact that categorical perception remains stable shows that differences in precision induced by factors as diverse as hearing level and literacy do not interfere with the phonological determination of the categories. Such phonological determination is deeply anchored in the early stages of perceptual development. The linguistic environment introduces profound modifications on speech perception in early infancy, before one year of age (Werker & Tees, 1984), that consist in combining universal (language independent) features to perceive phonological (language specific) ones (Hoonhorst et al., 2009). Deficits in categorical perception, such as those evidenced in dyslexia, seemingly result from failures in the couplings between universal features (Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004). The fact that neither auditory impairments nor poor literacy achievement result in categorical perception deficits indicates that these factors do not affect the phonological processing of the features. Better hearing provides better sensory ingredients that ameliorates categorical precision without interfering with the phonological processing of the features. Similarly, improvements in literacy consolidates the links between letters and phonological categories without changing the processes that give access to these categories.

Future studies should aim at checking whether these results hold true for other consonant contrasts such as place of articulation. Studying the

precise nature of the changes in categorical precision induced by literacy more thoroughly is also important to grasp how exactly it impacts phoneme perception. It may help our understanding of why literacy strongly enhances the activation of brain regions involved in phonological processing. Indeed, studies using functional magnetic resonance imaging reported that activation of the planum temporale is much stronger in literate compared to non-literate individuals when listening to spoken sentences; this enhanced pattern of activation is observed in both adults (Dehaene et al., 2010) and children (Monzalvo & Dehaene-Lambertz, 2013). Future studies should investigate whether the planum temporale is the neural site of the behavioral differences in categorical precision that were evidenced in the present work.

Declaration of Competing Interest

None.

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Appendix A. Appendix

Average values of the speech perception indexes used in the computation of correlations. Standard deviations in brackets.

		Grade 2 children	Unschooling adults	Schooled adults
Slope	Mean	-5.59	-5.44	-5.82
	SD	[1.07]	[1.38]	[0.73]
	Range	-6to-0.92	-6to-1.07	-to-3.08
Categorical precision	Mean	1.97	1.91	2.66
	SD	[0.82]	[0.82]	[0.47]
	Range	0.28-3.28	0.44-3.16	1.71-3.28
Categorical perception index	Mean	1	1.27	0.97
	SD	[0.68]	[0.9]	[0.77]
	Range	0.01-2.61	0.01-3.13	0.04-3.12

Appendix B. Appendix

Values of the correlation coefficients (Kendall’s τ -b) between the speech perception indexes and performance on ancillary tests observed across the three groups of participants, and associated significance levels (Bonferroni-corrected). Significant correlations in bold.

		Age	Letter knowledge	Reading fluency	Average reading	Average phonological awareness	Average RAN
n		97	97	97	88	97	96
Categorical precision indexes	Slope	0	-0.17	-0.09	-0.10	-0.08	0.13
	Discrimination peak	0.06	0.30**	0.27**	0.30**	0.25**	-0.17*
Categorical perception index		0.08	-0.09	-0.16	-0.08	-0.13	0.03

* p < .05.
** p < .01

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