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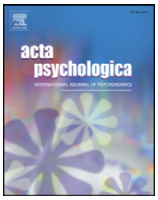

Lipread-induced phonetic recalibration in dyslexia

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ABSTRACT

Auditory phoneme categories are less well-defined in developmental dyslexic readers than in fluent readers. Here, we examined whether poor recalibration of phonetic boundaries might be associated with this deficit. 22 adult dyslexic readers were compared with 22 fluent readers on a phoneme identification task and a task that measured phonetic recalibration by lipread speech (Bertelson, Vroomen, & De Gelder, 2003). In line with previous reports, we found that dyslexics were less categorical in the labeling of the speech sounds. The size of their phonetic recalibration effect, though, was comparable to that of normal readers. This result indicates that phonetic recalibration is unaffected in dyslexic readers, and that it is unlikely to lie at the foundation of their auditory phoneme categorization impairments. For normal readers however, it appeared that a well-calibrated system is related to auditory precision as the steepness of the auditory identification curve positively correlated with recalibration.

1. Introduction

Developmental dyslexia (henceforth DD) is characterized by substantial reading problems that cannot be explained by education, motivation, and intelligence (American Psychiatric Association, 2000). Besides their reading problems, individuals with DD often also have deficits in auditory-phonological perception, phoneme representation, and phonological memory (see e.g. Vellutino, Fletcher, Snowling, & Scanlon, 2004 for a review). Indeed, numerous studies have reported that minimally contrasting speech categories (e.g., /b/ and /d/) are less well-defined in dyslexic than fluent readers (e.g. Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008; de Gelder & Vroomen, 1998; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Vandermosten et al., 2010; Werker & Tees, 1987), although group differences are not always observed (e.g. Blomert & Mitterer, 2004). Human speech, though, is not only perceived through sound but also through the visual information about the articulatory movements of the mouth and face, here referred to as 'lipreading'. It has been known for a long time that in daily life, lipread information helps to improve the eligibility of auditory speech (e.g. Sumby & Pollack, 1954). It is however less well-known that lipread speech not only disambiguates ongoing auditory speech, but also has a longer-term effect on sound identification as it can 'recalibrate' existing phonetic categories. On this view, lipread information is used to re-align existing sound categories so that the natural correspondence between what is heard and seen is maintained.

Phonetic recalibration by lipread speech has been demonstrated in a paradigm where repeated exposure to an auditory ambiguous speech sound (i.e., from the middle of an /aba/ – /ada/ continuum) in combination with clear lipread speech (i.e., a video of a speaker pronouncing either /aba/ or /ada/) elicits a shift of the phoneme boundary as measured in auditory-only post-tests (e.g. Bertelson, Vroomen, & De Gelder, 2003). Results show that an auditory ambiguous sound halfway between /b/ and /d/ is more likely perceived as /b/ when during the previous exposure phase, the same sound was combined with lipread /b/ rather than with lipread /d/. This finding has been taken as a demonstration that listeners flexibly adjust their phoneme boundary to include an ambiguous sound into a particular speech category based on previously encountered lipread information (e.g. Baart & Vroomen, 2010; Bertelson et al., 2003; van Linden & Vroomen, 2007; Vroomen, van Linden, de Gelder, & Bertelson, 2007; Vroomen, van Linden, Keetels, de Gelder, & Bertelson, 2004).

Given that previous studies have reported that individuals with DD may be impaired in phonetic sound categorization, we thought it important to examine to what extent DD-related deficits in auditory phoneme categorization are associated with poor phonetic recalibration. Of course, one can ask why one would expect a link between sound categorization and recalibration in the first place. We would argue that, in general, the phonetic speech recognition system has to meet two quite different requirements: On the one hand, it needs to be *precise* to make

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fine-grained distinctions between sounds that can be very similar, like the difference between a /b/ and a /d/. On the other hand, it also needs to be *flexible* so that it can adjust to acoustic variations between different utterances, speakers, environments, and so forth. Traditionally, these two requirements (precision and variability) have been studied in isolation (see for instance Samuel, 2011, for a review), but it seems plausible that both need to be handled at the same time while speech sounds are processed. It seems logical then, that a well-calibrated system can make better distinctions than a poorly calibrated system. For this reason, we expected listeners to be more precise in sound categorization, the better they were able to calibrate their phonetic system.

Starting from the observation that dyslexic readers have poor sound categorization, one can envisage various links between this skill and phonetic recalibration by lipread speech. One possibility, already alluded to, is that poor sound categorization is (partially) induced by a deficit in the ability to flexibly adapt the system based on visual speech cues, which, in turn, might be due to the fact that lipreading skills as such are compromised. This notion is in-line with reports showing that poor readers are also poor lipreaders (e.g. de Gelder & Vroomen, 1998; Mohammed, Campbell, Macsweeney, Barry, & Coleman, 2006). For instance, Mohammed et al. (2006) showed a deficit in lipreading in adult dyslexic readers when asked to match a lipread word, sentence, or short story with a picture.

If lipreading is indeed compromised, any necessary visually induced adjustments of auditory speech perception would be disturbed, which could result in poorer-defined auditory speech representations. Alternatively though, DD-related deficiencies in sound categorization might equally likely have an auditory origin, as the auditory speech deficits have been shown to already be present at birth. For example, newborns with familial risk for dyslexia display deviant brain activity (compared to non-risk infants) when presented with synthetic /ba/, /da/ and /ga/ sounds (Guttorm, Leppanen, Tolvanen, & Lyytinen, 2003; Leppanen, Pihko, Eklund, & Lyytinen, 1999), which in turn, is closely related to poor receptive language skills and verbal memory in the following years of development (Guttorm et al., 2005).

Yet another possibility is that dyslexic readers may have learned to compensate for their auditory deficits by relying more on lipread input, in line with a report showing that dyslexics display enhanced brain activity in areas dedicated to visual- and motor-articulatory processes as compared to controls when presented with audiovisual speech (Pekkola et al., 2006). On this view, it could well be that dyslexic readers would benefit more from disambiguating visual speech input than normal readers, which would lead to more observed recalibration for dyslexics than controls.

Since the literature does not seem to provide a definitive answer on whether lipreading is either impaired in dyslexic readers (e.g. Mohammed et al., 2006) or used to compensate for auditory deficits (Pekkola et al., 2006) we sought to obtain data on whether dyslexic readers actually use lipread information to calibrate their phonetic system like fluent readers do. Additionally, we investigated whether there is a relation between sound categorization and recalibration. For this, we adopted a paradigm described in Bertelson et al. (2003). Listeners were repeatedly exposed to a short block of audiovisual adapters that contained an auditory ambiguous sound halfway between /aba/ and /ada/ (the sound closest to the individually determined phoneme boundary, henceforth A?) that was combined with lipread (visual) information of /aba/ or /ada/ (i.e., the corresponding videos of a speaker pronouncing the VCV strings), resulting in two audiovisual stimuli with an ambiguous auditory component; A?Vb and A?Vd.

After a short exposure block to A?Vb or A?Vd, participants were tested on their identification of auditory-only sounds near their phoneme boundary. Recalibration should manifest itself as a higher likelihood to label the ambiguous sound as /b/ after exposure to A?Vb than after exposure to A?Vd. As a control for simple perseveration or priming effects, we included, as in previous studies, auditory non-ambiguous and audiovisual congruent exposure stimuli AbVb and AdVd. These stimuli typically yield no recalibration effect – because there is no conflict between what is heard and seen – but may yield a relatively small contrastive aftereffect due to selective speech adaptation because of the non-ambiguous nature of the sound (e.g. Eimas & Corbit, 1973). We incorporated two additional tasks in the experiment; a silent identification task of the visual speech stimuli and an auditory goodness-rating task of the exposure adapters. These tasks were administered to control for online perceptual group differences that could possibly confound the data of the aftereffects and were not intended to provide a reliable measure of lipreading skills. To rule-out the possibility that experimental results could be confounded by between-group variations in (non-) verbal intelligence, we compared dyslexic university students with normal reading university students. We expected that the DD-group would be less categorical than the controls in identifying auditory-only sounds, reflecting poorer-defined /b/ – /d/ speech categories. The critical question was whether the dyslexics would also display different recalibration effects, and whether there was correlation between these two measures.

2. Method

2.1. Participants

22 students (14 females) from Tilburg University, formally assessed and diagnosed with DD and 22 gender- and age-matched controls (from the same subject pool of university students) participated. All participants were native Dutch speakers between 18 and 25 years of age (Mean age was 20 years in both groups, $t(42)=.150$, $p=.882$). All reported normal hearing, had normal/corrected to normal vision, and gave their written informed consent prior to testing. All testing was conducted in accordance with the Declaration of Helsinki.

Before testing started, all participants were given two Dutch standardized tests that measured single word reading for real words and pseudo-words, namely the ‘Een-minuut-test’ (i.e. EMT, Brus & Voeten, 1997) and ‘De Klepel’ (van den Bos, Lutje Spelberg, Scheepsma, & De Vries, 1999). For both tests, we calculated the raw scores by subtracting the number of mistakes from the number of read items and results indicated, as expected, that the DD-group scored lower than the controls. The raw EMT scores were in between 53 and 101 for the dyslexics and in between 68 and 116 for the controls (averages were 74 and 100 respectively, $t(42)=7.04$, $p<.001$. The raw scores on De Klepel were in between 53 and 97 (mean = 68) for the DD-group vs. 73 and 116 (mean = 103) for the controls ($t(42)=9.28$, $p<.001$).

2.2. Stimuli

The stimuli were used before (Bertelson et al., 2003) and were adapted from audiovisual recordings (at 25 frames/second) of a male speaker of Dutch pronouncing the pseudo words /aba/ and /ada/. The audio was synthesized into a nine-token /aba/ – /ada/ continuum by changing the second formant (F2) in eight steps of 39 Mel (average F2 consonant frequency in the /aba/ continuum-endpoint was 1100 Hz, vs. 1680 Hz for the /ada/ endpoint) using the ‘Praat’ speech editor (Boersma & Weenink, 1999). To ensure accurate timing between sound and vision, videos were displayed as two strings of bitmaps (each bitmap displayed for 40 ms at a refresh rate of 100 Hz) while the sound was delivered by trigger, thus preserving the original timing. To induce recalibration, the individually determined most ambiguous sound of the continuum (A?) was combined with the video of /aba/ (Vb) or /ada/ (Vd), resulting in two audiovisual adapters; A?Vb and A?Vd. As a control, we included the audiovisual congruent adapters AbVb and AdVd that consisted of the auditory non-ambiguous endpoints of the continuum with the corresponding video.

2.3. Procedure and design

Participants were tested individually in a dimly lit and sound attenuated booth. Participants sat at approximately 70 cm from a 17-inch CRT-monitor. The audio was delivered at ~62 dBa (ear level) via two regular computer speakers (JBL Media 100).

The total experimental procedure lasted about 45 min and consisted of four phases: a silent visual /b/ – /d/ identification task, an auditory /b/ – /d/ identification task to test sound categorization and to determine the individual phoneme boundary, an exposure – test phase to test recalibration, and an auditory goodness rating task of the audiovisual adapters.

2.3.1. Silent visual speech identification

To test whether there was any difference in identifying visual-only /aba/ and /ada/, we delivered Vb and Vd 12 times each in random order without sound. Following each stimulus presentation, participants decided whether they saw /aba/ or /ada/ being pronounced by pressing the corresponding key on a response box. The next stimulus was delivered 750 ms after key-press.

2.3.2. Auditory identification

The nine auditory tokens of the continuum were presented 12 times each in random order. On each trial, participants watched a fixation cross on the screen and indicated whether they heard /aba/ or /ada/ by pressing the 'b'- or 'd'-key. The next trial started 1000 ms after detection of the key-press. After testing, the perceptually most ambiguous token of the continuum was determined for each participant. This was done by fitting a cumulative function on the proportion of 'b'-responses. The stimulus closest to the 50% cross-over point served as the most ambiguous token (A?) in the following recalibration phase.

2.3.3. Exposure-test phase

Participants were repeatedly presented a short exposure block of audiovisual adapter stimuli followed by six auditory-only test trials. Each exposure block consisted of eight repetitions (ISI = 150 ms) of one of the four audiovisual adapters A?Vb, A?Vd, AbVb, and AdVd. Exposure was immediately (400 ms) followed by an auditory-only test in which participants indicated whether they heard /aba/ or /ada/ by pressing a corresponding key. The auditory test stimuli were A?, its more 'aba-like' neighbour on the continuum (A?-1), and the more 'ada-like' neighbour on the continuum A? + 1. These three auditory tokens were delivered twice each in random order (six test trials, ITI = 1000 ms). In total, 32 of these short exposure – test blocks were delivered in random order (8 blocks per audiovisual adapter). To ensure that participants attended the screen during exposure, occasional catch-trials consisting of a small white dot above the upper lip of the speaker (Ø~3 mm, 120 ms in duration) had to be detected by pressing a designated key.

2.3.4. Goodness rating of audiovisual adapters

To ensure that the exposure stimuli A?Vb, A?Vd, AbVb, and AdVd were perceived in a similar way by all participants, we asked them, at the end of the experiment, to rate the /b/ – /d/ quality of the auditory signal of the audiovisual adapters on a 7-point Likert-scale with '1' representing a clear /b/ and '7' a clear /d/. Responses were collected with a keyboard and the next trial started 1200 ms after key press. All four adapters were presented eight times in pseudorandom order (32 trials in total).

3. Results

3.1. Identification of lipread stimuli

The data of the visual-only task were analyzed by measuring the proportion of correct responses (a 'b'-response after Vb, and a 'd'-responses after Vd). A 2 (Video identity: Vb vs. Vd) × 2 (Group: DD's vs. controls) ANOVA on these data showed no main effect of video-identity (*F*-value < 1) as both videos were correctly identified in 98% of the trials. There was no main effect of group ($F(1,42) = 2.02$, $p = .163$) and no interaction between video-identity and group ($F(1,42) = 1.17$, $p = .285$), indicating that discrimination of visual speech /b/ from /d/ was alike in both groups and at ceiling.

3.2. Auditory identification

For the auditory identification test, we measured the proportion of 'b'-responses for each token of the continuum. A 9 (Auditory token) × 2 (Group) ANOVA showed a main effect of auditory token ($F(8,336) = 465.69$, $p < .001$) because unsurprisingly, there were more 'b'-responses for the more 'b-like' tokens of the continuum. The overall proportion of 'b'-responses was lower for the DD-group than for the controls (.42 vs. .48 respectively, $F(1,42) = 5.20$, $p < .028$), and there was an interaction between auditory token and group ($F(8,336) = 2.16$, $p < .031$). To examine this interaction in more detail, we fitted a logistic function on the individual raw data (see Fig. 1). The fitted functions, on average, could explain 84% of the observed variance in the dyslexic group vs. 87% in the normal reading group ($t(42) = 1.39$, $p = .173$, all individual R^2-values > 65%), indicating that our fitted functions were good estimates. This allowed us to determine the 50% cross-over point, reflecting the /b/ – /d/ phoneme boundary, and the slope values of the logistic functions as a measure of categoricalness of the auditory classification.

The analyses showed that the DD-group had their phoneme boundary located more towards the /b/-end of the continuum (at 4.29 stimulus units) than the control group (4.83 units), $t(42) = 2.40$, $p < .022$. As anticipated, dyslexics also had shallower slopes than the control group, ($t(42) = 2.19$, $p < .035$, see also Fig. 1.), thus indicating that the DD-group was less categorical in labelling the sounds of the continuum than the control group.

3.3. Exposure-test

The overall proportion of detected catch-trials (95%) was alike in both groups ($t(42) = .77$, $p = .446$), indicating that both the dyslexic and fluent readers were paying attention to the screen during exposure.

The critical data of the exposure–test phase are presented in Table 1. The data were analyzed as in previous studies by computing aftereffects (e.g. Bertelson et al., 2003), thereby pooling the proportion of 'b'-responses over the three test tokens (see Table 1). As expected, after exposure to auditory ambiguous sounds there were substantially

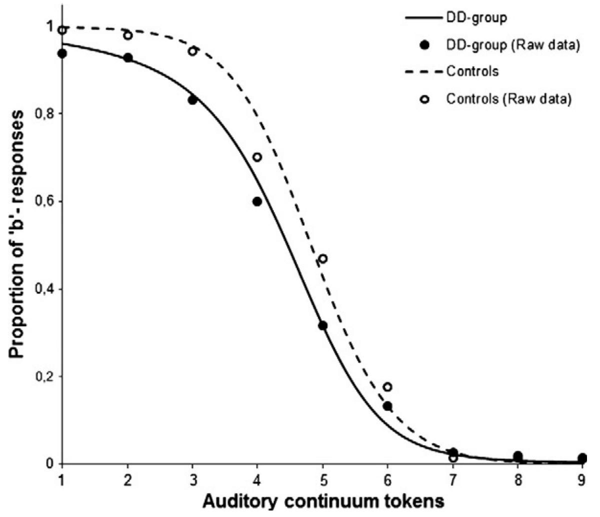

Fig. 1. Proportion of 'b'-responses on the auditory continuum tokens for the DD- and control group.

more 'b'-responses after exposure to A?Vb than A?Vd, thus reflecting the basic recalibration effect (a 31% overall difference). For the auditory non-ambiguous control adapters AbVd and AdVd, there was no statistical reliable difference and listeners were equally likely to report /b/ after exposure to AbVb or AdVd. Most importantly, these aftereffects did not differ between the two groups.

These generalizations were confirmed in a 2 (Sound ambiguity: auditory ambiguous vs. auditory non-ambiguous adapters) × 2 (Group) ANOVA on the aftereffects. There was a main effect of sound ambiguity ($F(1,42) = 108.29$, $p < .001$), with no main effect of group ($F(1,42) = 1.81$, $p = .186$), and no interaction between the two factors (F-value < 1).

Separate t-test confirmed that aftereffects were bigger than zero for adapters containing ambiguous sounds, reflecting recalibration (DD-group: a 33% aftereffect, $t(21) = 9.94$, $p < .001$; Controls: a 29% aftereffect, $t(21) = 5.55$, $p < .001$), but not for adapters containing auditory non-ambiguous sounds (both p-values $> .110$).

We also examined the correlation (Pearsons ρ) between the size of the lipread-induced recalibration effect and the slope of the identification curve. For normal readers, recalibration effects were correlated with slope ($\rho = .48$, $p < .025$), indicating that the more 'categorical perceivers' (steeper slopes) had larger recalibration effects. This however, was not the case for the DD-group ($\rho = -.16$, $p = .471$). This group difference in correlation was significant ($p < .035$ after a Fisher z transformation).

3.4. Goodness ratings

To analyze the auditory goodness ratings of the exposure stimuli, we computed the average rating per adapter. The 2 (Sound ambiguity) × 2 (Video identity) × 2 (Group) ANOVA showed no main effect of sound ambiguity ($F < 1$). As expected, there was an effect of video identity ($F(1,42) = 1772.45$, $p < .001$) because videos containing /aba/ were rated more 'b'-like than videos containing /ada/ (1.43 vs. 6.12 respectively). This effect was modulated by adapter ambiguity ($F(1,42) = 62.88$, $p < .001$) as the auditory unambiguous adapters were rated more towards the endpoints of the scale (i.e. as better examples) than the adapters containing auditory ambiguous sounds. The ANOVA showed no main effect of group ($F < 1$), nor did group interact with any (combination) of the other factors (all p-values $> .097$). This result indicates that the audiovisual adapters were, as intended, perceived in a similar way by dyslexic and normal readers.

4. Discussion

Dyslexic readers were compared with fluent readers on a /b/ – /d/ sound identification task and a task that measures phonetic recalibration by lipread speech. The data regarding sound identification demonstrated that dyslexic readers were less categorical in labeling the speech sounds from the /b/ – /d/continuum than the control group. This result confirms previous studies that indicate that dyslexic readers have poorer-defined phonetic sound categories than fluent readers (e.g. Bogliotti et al., 2008; de Gelder & Vroomen, 1998; Godfrey et al., 1981; Vandermosten et al., 2010; Werker & Tees, 1987). The new finding here is that phonetic recalibration by lipread information was intact in the DD-group as the amount of recalibration was comparable in size with that of normal readers. At first sight, it thus seems conceivable that the dyslexics' deficits in the categorization of auditory speech are unlikely to originate from an inability to recalibrate the phonetic system.

Table 1
Proportion of 'b'-responses for the DD-group and the controls after exposure to four different audiovisual adapters and the corresponding aftereffect.

Group	Sound quality	Visual information		Aftereffect
		Vb	Vd	
DD	Ambiguous	.55	.22	.33*
	Non-ambiguous	.44	.43	.01
Control	Ambiguous	.55	.26	.29*
	Non-ambiguous	.45	.51	-.06

*$p < .001$.

Another finding was that the DD-group was not impaired in visual-only identification of lipread /b/ and /d/, as the visual-only performance of both groups was alike and almost flawless (98% correct). The goodness ratings of the audiovisual adapters also showed that both groups were equally affected by the visual input. Most likely then, both groups were equally good in lipreading the stimuli used here. This may seem remarkable because in a previous study on the recognition of audiovisual speech, de Gelder and Vroomen (1998) have used the same phonetic /b/ – /d/ contrast (although different stimuli), and reported considerably lower proportions of correctly lipread responses in both a poor- (.67) and a normal reading group (.77). A potentially relevant difference though, is that this study tested dyslexic children rather than adults. It is well-known that children are less proficient decoders of lipread speech (e.g. McGurk & MacDonald, 1976) and this developmental trend in the effective use of lipread information is further underscored by a more recent study (that used the same stimuli and procedures as here) that showed that lipread-induced phonetic recalibration develops with age (van Linden & Vroomen, 2008).

However, despite the lack of group differences in the overall data, it is of note that the correlation between auditory sensitivity (slopes of the fitted curves) and the amount of recalibration reflects a rather interesting dissociation between the two groups. Normal readers with well-defined speech categories (i.e., steep slopes) had large lipread-induced aftereffects indicative of recalibration whereas this was not the case for the dyslexic readers. It seems logical that high auditory perceptual ambiguity yields larger perceptual shifts (following the principle of inverse effectiveness), but current data reflect the opposite, in line with our suggestion, namely that a well-calibrated system can make better distinctions than a poorly calibrated system. On this view, *precise* auditory perception is linked with *flexibility*. Since recalibration is driven by the visual input, it seems conceivable that lipread-induced recalibration is related to the extent that perceivers are actually able to lipread the stimuli and the suggestion that poor readers are also poor lipreaders (e.g. de Gelder & Vroomen, 1998; Mohammed et al., 2006) might explain why there was no link between auditory categoricalness and recalibration in the dyslexic group. Admittedly though, this should be interpreted with caution given that the group-averages regarding recalibration, the goodness ratings and visual only speech identification were alike and we thus obtained no behavioral evidence that lipreading abilities were impaired in the DD-group.

To conclude, the data of the DD-group showed normal recalibration effects while auditory categorization was compromised. This suggests that dyslexia-related impairments in auditory phoneme categorization do most likely not originate from an inability to recalibrate the phonetic system. Interestingly, though, there was dissociation between normal and dyslexic readers in auditory categorization and recalibration: In normal readers, more categorical perceivers were also more calibrating the phonetic system, while in the dyslexic group this was not the case. It remains for future studies to explore whether this profile holds with a wider sample of dyslexics than the ones used here. Conceivably, dyslexic readers who are able to attend university have milder literacy and language deficits (or are better able to compensate them) than those typically observed in the larger dyslexic population. One possible way to tap into this would be by testing a group of dyslexic children rather than adults. One caveat, though, is that one needs to take into account that there is a developmental trend in the use of lipread information that might easily moderate the lipread-induced recalibration effects obtained with children.

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