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Research Article

A General Audiovisual Temporal Processing Deficit in Adult Readers With Dyslexia

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Purpose: Because reading is an audiovisual process, reading impairment may reflect an audiovisual processing deficit. The aim of the present study was to test the existence and scope of such a deficit in adult readers with dyslexia.
Method: We tested 39 typical readers and 51 adult readers with dyslexia on their sensitivity to the simultaneity of audiovisual speech and nonspeech stimuli, their time window of audiovisual integration for speech (using incongruent /aCa/ syllables), and their audiovisual perception of phonetic categories.
Results: Adult readers with dyslexia showed less sensitivity to audiovisual simultaneity than typical readers for both speech and nonspeech events. We found no differences between readers with dyslexia and typical readers in the temporal window of integration for audiovisual speech or in the audiovisual perception of phonetic categories.
Conclusions: The results suggest an audiovisual temporal deficit in dyslexia that is not specific to speech-related events. But the differences found for audiovisual temporal sensitivity did not translate into a deficit in audiovisual speech perception. Hence, there seems to be a hiatus between simultaneity judgment and perception, suggesting a multisensory system that uses different mechanisms across tasks. Alternatively, it is possible that the audiovisual deficit in dyslexia is only observable when explicit judgments about audiovisual simultaneity are required.

Developmental dyslexia is characterized by severe difficulties in attaining an adequate reading level despite normal intelligence and educational opportunities and in the absence of any sensory or neurological impairment (Lyon, Shaywitz, & Shaywitz, 2003). Phonemic awareness and letter knowledge have been consistently found to be prerequisites of reading ability (Bowey, 2005; Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012; Melby-Lervåg, Lyster, & Hulme, 2012). This could be because both are pivotal to the learning and storing of mappings between visual symbols (graphemes) and letter sounds (phonemes; Melby-Lervåg et al., 2012). Learning and automatization of those mappings—concerning, fundamentally, audiovisual objects—are crucial for literacy acquisition (Ehri, 1998). Indeed, a failure in the letter-sound mapping system is considered to be a main cause of developmental dyslexia (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Because reading is thus an audiovisual mapping process, developmental dyslexia may reflect a general audiovisual processing deficit rather than a specific deficit in processing letter–sound mappings. In this study, we tested for the existence of such a deficit in dyslexia, focusing on three aspects in which readers with dyslexia and typical readers could differ: in the time window over which auditory and visual events are perceived as synchronous, in the time window over which events are integrated into a unitary percept in audiovisual speech perception, and in phonetic identification of audiovisual speech.

Readers with dyslexia inadequately process letter–sound associations. During the processing of letters and speech sounds, adults (Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009; Kast, Bezzola, Jäncke, & Meyer, 2011), adolescents (Kronschnabel, Brem, Maurer, & Brandeis, 2014), and children (Blau et al., 2010) with dyslexia have been found to underactivate brain regions involved in

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grapheme–phoneme conversions (i.e., the left inferior frontal and angular gyri; Kronschnabel et al., 2014) and areas of the brain associated with multisensory integration, such as the supramarginal gyrus (Kast et al., 2011) and superior temporal regions (Blau et al., 2009, 2010; Kast et al., 2011; Kronschnabel et al., 2014). Electrophysiological studies measuring mismatch negativity (MMN) provide further evidence for a difference between readers with dyslexia and typical readers in their processing of letter–speech sound associations. The MMN is evoked in an oddball paradigm when, in a sequence of auditory stimuli, a rarely presented sound (the deviant) deviates from a frequently presented sound (the standard). Typical readers showed an enhancement of the MMN in response to deviant spoken syllables compared with standards when letters were presented with the speech stimuli (Froyen, Willems, & Blomert, 2011) but not when scrambled images were presented with the speech (Mittag, Thesleff, Laasonen, & Kujala, 2013). This enhancement of the MMN was absent in children with dyslexia (Froyen et al., 2011) and adults (Mittag et al., 2013). The lack of enhancement of the MMN in people with dyslexia suggests that early and automatic letter–speech sound integration is absent (Froyen et al., 2011; Mittag et al., 2013).

The focus in these studies has mostly been on letter–speech sound associations. Some have argued that letter–speech sound audiovisual objects are special and that the difficulties with letter–sound associations in readers with dyslexia should not generalize to other audiovisual objects (Blomert, 2011; Blomert & Froyen, 2010). But there is evidence suggesting that readers with dyslexia also differ from typical readers when processing nonlinguistic audiovisual material. In an electrophysiological study, children with dyslexia and typical children indicated whether visual and auditory patterns (rectangles and tones) were congruent or incongruent (Widmann, Schröger, Tervaniemi, Pakarinen, & Kujala, 2012). Compared with their controls, children with dyslexia showed a later and smaller N2b, no P3a, and no early-induced auditory gamma band response when sounds and symbols were congruent. In addition, the N2b amplitude was significantly correlated with reading skill. The N2b is evoked in response to deviant task-relevant stimuli, and it is interpreted as reflecting processes related to attentive target discrimination (Näätänen, 1992). Widmann et al. (2012) suggested that the later onset and lower amplitude of N2b found in children with dyslexia could reflect later and less reliable processing of audiovisual congruency. The P3a is evoked in response to novel and salient sounds (Wetzel & Schröger, 2007) and has been related to the behavioral relevance of a stimulus (Widmann et al., 2012). Therefore, the absence of the P3a in readers with dyslexia suggests the presence of impaired audiovisual identification processes. Last, early-induced auditory gamma band responses that reflect the synchronization of neural activity have previously been related to the integration of visual and auditory information (Widmann, Gruber, Kujala, Tervaniemi, & Schröger, 2007). Widmann et al. (2012) argued that the absence of an early-induced auditory gamma band response in readers with dyslexia indicates no or less integration of audiovisual information into unitary audiovisual objects. Further evidence for differences between readers with dyslexia and typical readers in processing audiovisual nonspeech materials comes from a behavioral study by Harrar et al. (2014) on the multisensory facilitation of reaction times in adult readers with dyslexia. The extent to which responses to audiovisual stimuli (a white noise burst and a Gabor patch) were speeded compared with responses to unisensory stimuli was smaller in the dyslexia group. The magnitude of the reduction of this multisensory benefit was related to reading ability in both groups. Again, the ability to benefit from audiovisual events and reading ability seem to be related.

In summary, these results suggest that the audiovisual deficit in dyslexia might be of a more general nature and not confined to letter–speech sound associations or even to the language domain. This impaired multisensory integration is not only observable in children with dyslexia but—like dyslexia itself (e.g., Elbro, Nielsen, & Petersen, 1994)—persists in adulthood. It is thus not a transient developmental lag associated with the beginning of reading acquisition. It is relevant to characterize the scope of the deficit in adult readers with dyslexia.

So far, the nature of an audiovisual deficit in dyslexia has only been explored with either letter–sound associations (e.g., Kronschnabel et al., 2014) or nonlinguistic events (e.g., Harrar et al., 2014). Although the use of nonlinguistic materials contributes to the conceptualization of the audiovisual deficit as a domain-general phenomenon, these materials were often not ecologically valid. By using ecologically valid nonlinguistic stimuli (clapping) and linguistic stimuli (audiovisual speech), we assessed if and in what way the combination of auditory and visual information is deficient in readers with dyslexia. This allows for using ecologically valid materials that refer to a unitary audiovisual event while avoiding probing the direct area of difficulty: letter–sound associations (i.e., reading).

An audiovisual processing deficit might manifest in at least three different ways. First, the time window over which auditory and visual events are perceived as occurring simultaneously might differ between readers with dyslexia and typical readers. This audiovisual temporal sensitivity is assessed in tasks in which participants have to judge explicitly the temporal order of auditory and visual events (using a temporal-order judgment task) or their simultaneity (using a simultaneity judgment task). Temporal synchrony is one of the most important determinants of whether or not two events in different modalities are perceived as one multisensory event or as two separate events (e.g., Stein & Meredith, 1993). Human observers tolerate asynchronies between auditory and visual signals up to several hundred milliseconds and still judge them as synchronous (Conrey & Pisoni, 2006; Dixon & Spitz, 1980; Massaro, Cohen, & Smeele, 1996; McGrath & Summerfield, 1985; van Wassenhove, Grant, & Poeppel, 2007). The time window over which auditory and visual events are perceived as occurring simultaneously is asymmetric: Leading auditory information is already detected at small stimulus onset asynchronies (SOAs), but leading visual information needs larger asynchronies before it is detected (e.g., Grant & Greenberg, 2001; van Wassenhove et al., 2007). Moreover, this time window differs across stimuli with wider temporal windows for complex (e.g., speech) than simple (e.g., tones and flashes) stimuli (e.g., Vatakis & Spence, 2006). This time window seems to be wider for readers with dyslexia than for typical adult readers when judging the cross-modal temporal order of auditory and visual nonspeech events (tones and circles; Hairston, Burdette, Flowers, Wood, & Wallace, 2005). According to Hairston et al. (2005), this extended window could result in difficulties in processes that are dependent on the rapid and accurate integration of cues from multiple senses, such as reading. Hairston et al. argued that expanding the temporal window over which auditory and visual events are seen as synchronous will likely result in inappropriate grapheme–phoneme correspondences and, as a consequence, in less efficient decoding. Wallace and Stevenson (2014) added that extended temporal windows might lead to difficulties in the construction of strong reading representations, in that the windows will cause greater ambiguity in the correspondences between the auditory and visual elements of words. As an alternative, readers with dyslexia may experience difficulties in the uptake of information and extend their temporal windows to compensate for the difficulties in sensory processing (see, for example, Diederich, Colonius, & Schomburg, 2008; Laurienti, Burdette, Maldjian, & Wallace, 2006, for a similar suggestion regarding older adults). Either way, the idea that abnormally wide temporal windows could result in deficits in processes that require narrow windows (i.e., reading; see Froyen, van Atteveldt, Bonte, & Blomert, 2008) warrants further investigation.

A second way an audiovisual processing deficit might manifest is in the size of the time window over which audiovisual information is combined into a unitary percept. In the present study, we test this time window of integration for audiovisual information in /aCa/ syllables that elicit the *McGurk effect*. The McGurk effect is a perceptual illusion that shows the influence of visual speech information on the perception of speech (McGurk & MacDonald, 1976). It has been commonly used as a way to assess audiovisual speech integration (Alsius, Navarra, Campbell, & Soto-Faraco, 2005; Alsius, Navarra, & Soto-Faraco, 2007; Munhall & Tohkura, 1998; Soto-Faraco & Alsius, 2007; Tiippana, Andersen, & Sams, 2004; van Wassenhove, Grant, & Poeppel, 2005; van Wassenhove et al., 2007; but see Tiippana, 2014). It is characterized by a change in auditory perception induced by incongruent visual speech: When hearing the syllable /apa/ while seeing a speaker pronouncing /aka/, participants typically tend to report perceiving /ata/ (this is labeled a *fusion response*). In this case, the alveolar /t/ best matches the contradictory place of articulation information provided by the visual velar /k/ and the auditory bilabial /p/. In tasks with McGurk stimuli with various SOAs, typical readers show a temporal window of integration of approximately 200 ms (Conrey & Pisoni, 2006; Munhall, Gribble, Sacco, & Ward, 1996; Soto-Faraco & Alsius, 2007; van Wassenhove et al., 2007). To the best of our knowledge, the width of the temporal window of integration has not been examined in readers with dyslexia.

The two time windows—the one used to judge simultaneity and the one during which audiovisual integration occurs—may or may not be related. One possibility is that there is a correlation between audiovisual temporal sensitivity and audiovisual perception (Baskent & Bazo, 2011; Grant & Seitz, 1998; Stevenson, Zemtsov, & Wallace, 2012). For instance, Stevenson et al. (2012) reported that individuals with narrower windows of audiovisual integration were better in dissociating asynchronous audiovisual sound-flashes events than individuals with wider windows. A different possibility is that there is a dissociation between temporal sensitivity and perception (Conrey & Pisoni, 2006; Soto-Faraco & Alsius, 2007, 2009; van Wassenhove et al., 2007). Soto-Faraco and Alsius (2009) showed that there were regions of a SOA continuum where individuals predominantly responded that audio and video were asynchronous but still reported a significant number of fusion percepts. Furthermore, the brain network involved in the detection of simultaneity has been shown to differ from that involved in integration (Miller & D'Esposito, 2005). In sum, it is not yet clear if the two time windows are related—that is, if an individual who judges events as simultaneous over a wider temporal window also integrates audiovisual events over a similarly extended window. We will therefore test whether readers with dyslexia and typical readers differ in both or only one of these windows.

Third, readers with dyslexia and typical readers might differ in the extent to which their perception of speech sounds is influenced by information from the auditory and visual modalities. Several approaches have been used to examine this possibility. One approach is to determine if the phonetic categories of readers with dyslexia and typical readers differ. De Gelder and Vroomen (1998) assessed differences between 9- and 14-year-old poor readers and their age- and reading-level matched controls in an audiovisual phonetic categorization task. Nine steps from an auditory and visual continuum between /ba/ and /da/ were presented unimodally or combined into audiovisual speech. The readers with dyslexia were less categorical in the identification of auditorily presented stimuli and poorer at speechreading. However, the influence of visual information on audiovisual speech perception did not differ between groups—that is, audiovisual speech perception seemed to be reasonably intact. Baart, de Boer-Schellekens, and Vroomen (2012) compared audiovisual speech perception abilities of adults with dyslexia and typical readers using a phoneme identification task before and after the recalibration of auditory phonetic categories through visual speech information. In line with the previous evidence, readers with dyslexia were less categorical in the labeling of the speech sounds, but the size of their phonetic recalibration effect was the same as that of typical readers.

A second approach used to study potential differences in speech perception in readers with dyslexia versus typical readers is to assess the size of the audiovisual benefit. Speech is typically perceived more accurately when participants hear and see the speaker than when they only hear the speaker (e.g., Arnold & Hill, 2001; Jesse, Vrignaud, Cohen, & Massaro, 2000; MacLeod & Summerfield, 1987; Reisberg, McLean, & Goldfield, 1987; Spehar, Tye-Murray, & Sommers, 2008; Sumby & Pollack, 1954). This audiovisual benefit arises because visual speech provides information that is complementary and redundant to that of auditory speech (Grant, Walden, & Seitz, 1998; Jesse & Massaro, 2010; Sumby & Pollack, 1954; Summerfield, 1987; Walden, Prosek, & Worthington, 1974). Adult readers with dyslexia do not benefit from visual cues as much as typical readers (Ramirez & Mann, 2005), but one has to be cautious about the locus of the effect. In Ramirez and Mann's (2005) study, readers with dyslexia were also poorer than their controls at identifying visual cues when presented in isolation. The deficit could thus be at the level of processing visual speech rather than at the integration level. In line with this, children with dyslexia show the same size of audiovisual benefit as typically developing children once differences in the processing of auditory and visual stimuli are taken into consideration (Campbell, Whittingham, Frith, Massaro, & Cohen, 1997). This suggests that even though the processing of auditory and visual speech in readers with dyslexia may be less efficient, integration itself does not seem to be impaired. In accordance with this, Megnin-Viggars and Goswami (2013) reported that for readers with dyslexia and typical adult readers who showed similar performance in visual speech perception, the size of the audiovisual benefit was the same. The performance of both groups in the audiovisual condition was, however, near ceiling, which could suggest that the task was not sensitive enough to reveal group differences.

Last, audiovisual speech perception can also be assessed using McGurk stimuli. Hayes, Tiippana, Nicol, Sams, and Kraus (2003) showed that children with learning disabilities and typically developing children performed similarly on McGurk stimuli in low- and no-noise conditions. However, in a more difficult listening situation with a high level of noise, individuals with learning disabilities gave more visually based responses and fewer fusion responses than typically developing children. The difference in fusions could not be accounted for by unisensory differences. Groen and Jesse (2013) compared children and adolescents with dyslexia and their age-matched controls. There were no unisensory visual or auditory differences between the groups. Moreover, children and adolescents with dyslexia did not differ from the typical readers in their perception of McGurk stimuli. Other studies showing unisensory differences (Bastien-Toniazzo, Stroumza, & Cavé, 2010; Cavé, Stroumza, & Bastien-Toniazzo, 2007) or not reporting unisensory performance (Boliek, Keintz, Norrix, & Obrzut, 2010; Norrix, Plante, & Vance, 2006) found mixed results in terms of whether or not children with dyslexia reported fewer or the same amount of fusion responses. These results are difficult to interpret, however, because group differences in the size of the McGurk effect could arise from differences in performance either in unimodal conditions and/or in audiovisual processing.

In summary, typical readers and readers with dyslexia may differ in audiovisual temporal sensitivity, in the temporal window of integration, and/or in the audiovisual speech perception of phonetic categories. However, despite the plausible link between audiovisual processing and reading ability, the evidence is still scarce, may not be generalizable to the processing of ecologically valid materials, and is not always consistent. In addition, studies often focus on only one component of audiovisual processing, which does not allow for a broader characterization of the audiovisual processing profile in dyslexia. In our study, we tested the hypothesis that an audiovisual processing deficit may underlie reading impairment. Our intentions were fourfold. First, we tested for differences in audiovisual temporal sensitivity—that is, if the time window over which auditory and visual events are perceived as occurring simultaneously is different between readers with dyslexia and typical readers. Adult typical readers and readers with dyslexia performed a simultaneity judgment task with ecologically valid speech (McGurk) and nonspeech (clapping) stimuli with different SOAs. We used both speech and nonspeech events to reveal whether any possible deficits in readers with dyslexia compared with typical readers are restricted to speech or are domain-general. Second, we determined if readers with dyslexia and typical readers differ in the size of the temporal window of integration for audiovisual speech. The same participants were tested in a speech identification task, again using McGurk stimuli with different SOAs. Third, we tested for group differences in phonetic identification of consonants placed in audiovisual nonsense syllables. We asked if differences would emerge between typical readers and readers with dyslexia in the identification of McGurk stimuli and in the phonetic categorization of steps from an audiovisually presented continuum between two phonetic categories. This allowed us to test if a change in the size of the audiovisual time window(s) in dyslexia, if present, also affects speech perception. Fourth, we compared these three aspects of audiovisual processing in the same individuals and hence can provide a broader profile of the differences, if any, between readers with dyslexia and typical readers.

Method

Participants

Fifty-four typical readers and 60 readers with dyslexia were recruited. All participants were undergraduate students at the Radboud University or at the HAN University of Applied Sciences in Nijmegen and received monetary compensation or course credits for their participation.

All participants had normal or corrected-to-normal vision and were native speakers of Dutch. The inclusion of a participant in the group of readers with dyslexia or typical readers was contingent on whether or not participants had a prior diagnosis of dyslexia and on their performance on a reading task we administered (the task is described in the Reading and Cognitive Measures section). On the basis of the distribution of the scores, the following cutoffs were chosen: To be considered typical readers, participants had to perform not only above the 50th percentile on reading accuracy, but also above the 30th percentile on reading speed. To be included in the readers with dyslexia group, participants had to perform below the 50th percentile on reading accuracy or below the 30th percentile on reading speed. Fourteen typical readers and three readers with dyslexia, as originally defined, were excluded from the initial sample because their performance did not meet these criteria.

In addition, to be included in the final sample, all participants had to show pure-tone thresholds in a standard audiometric test below 30 dB HL in each ear for a range of frequencies (0.125 to 4 kHz). One typical reader and six readers with dyslexia (as originally defined) were excluded from further analyses for not meeting threshold in this hearing screening.

Therefore, 39 typical readers (nine men, 30 women; age $M = 22.3$, $SD = 2.9$ years) and 51 readers with dyslexia (11 men, 40 women; age $M = 22.7$, $SD = 2.7$ years) were included in the final sample. The median for typical readers was the 75th percentile (range = 54th to 99th percentile) in reading accuracy and the 76th percentile (range = 37th to 99th percentile) in reading speed. The median for readers with dyslexia was the 19th percentile (range = 1st to 65th percentile) in reading accuracy and the sixth percentile (range = 1st to 92nd percentile) in reading speed.

Reading and Cognitive Measures

Reading

Reading was assessed with the text-reading task from a standardized Dutch reading and writing battery for dyslexia diagnosis in adolescents and adults (Test voor gevorderd Lezen en Schrijven; Depessemier & Andries, 2009). Participants were asked to read a 582-word text out loud while being audiorecorded. This text consisted of three paragraphs, varying in reading difficulty (easy, medium, and difficult). Silent prereading of the text was not allowed. Despite being informed that the time taken to read the text would be considered, the participants were told that it was more important to read clearly and accurately than to read fast. If more than 5 s were taken to read a word, the experimenter would read the word out loud. The participant would then continue reading, starting with the following word. Number of errors and time needed to complete the task were measured. Omissions, additions, replacements, and inversions were coded as errors, following the test manual, and the total number of errors per participant was calculated. The time to complete the task was the total time in seconds taken to read the entire text. The raw scores of the two measures (number of errors and time) were transformed into percentiles using the norms provided in the test manual to determine group membership. However, for the statistical analyses, we used the raw scores for both measures.

Nonverbal Cognitive Ability

Matrix Reasoning, a subtest of the Dutch adaptation of the Wechsler Adult Intelligence Scale–Fourth Edition (Wechsler, 2012), was used to assess nonverbal cognitive ability. Participants viewed an incomplete matrix of abstract pictures and were asked to select, from five possibilities, the picture that best completed the matrix. Items were presented until the participant made four consecutive errors or four errors on five consecutive items, or until the end of the task was reached. The number of correct responses was used to compute a standardized score ($M = 10$, $SD = 3$).

Speechreading

Speechreading was assessed with a forced-choice, visual-only syllable identification task taken from Jesse and Janse (2012). The stimuli consisted of 10 consonant–vowel syllables. The consonants came from five Dutch viseme classes (bilabial: /p/, /m/; labiodental: /f/, /v/; nonlabial front fricatives: /s/, /z/; other nonlabial front consonants: /t/, /n/; and other nonlabial back consonants: /k/, /x/; van Son, Huiskamp, Bosman & Smoorenburg, 1994). The vowel was the same for all syllables (/ø/). A total of six blocks was presented. Each block consisted of 10 silent videos of a speaker's face pronouncing each of the consonant–vowel syllables, presented in random order. After each video, the set of possible responses was shown on the screen. The participants were asked to indicate which consonant (out of 10) the speaker had produced by pressing the corresponding key on a computer keyboard. If a response was not given in 5 s, the next video was presented. No feedback was provided. Overall accuracy (proportion of correct answers) was computed.

Experimental Materials and Procedures

Simultaneity Judgment Task

Audiovisual speech and nonspeech materials were created to assess audiovisual temporal sensitivity in a simultaneity judgment task. Speech materials were taken from Groen and Jesse (2013) and consisted of a McGurk stimulus in which the auditory syllable /apa/ was dubbed onto a video showing a speaker saying /aka/. This stimulus should thus be perceived by participants as /ata/ (McGurk & MacDonald, 1976). Nonspeech materials consisted of a video showing a woman clapping her hands. The hands were clapped above the head so that only the hands and wrists were visible. The time between the start of the visual event (the beginning of the mouth or the hand moving) and the auditory event (the onset of the first phoneme or of the clapping sound) was approximately 200 ms in the initial recordings of both types of materials. White noise was added to the speech stimuli at −16 dB signal-to-noise ratio (SNR) to increase the possibility of fusion (Groen & Jesse, 2013).

To create these stimuli, a female native Dutch speaker was videorecorded pronouncing the syllables /apa/ and /aka/ (Groen & Jesse, 2013), and the first author was recorded clapping hands. Speech stimuli were recorded with a Sony DCR-HC1000E camera and nonspeech stimuli with a Sony Handycam DCR-SR190E. The audio was recorded at 44.1 kHz. The videos were digitized as uncompressed 400 × 320 .avi files in PAL format. Videos were edited using Adobe Premiere Elements 11.0 (Adobe Systems, Mountain View, CA) and Praat (Boersma & Weenink, 2013). For speech and nonspeech stimuli, the time between the onset of the visual and of the auditory event (SOA) was systematically varied. To create stimuli with various SOAs, the video track of each stimulus was systematically shifted in 40-ms increments (i.e., by one frame) so that the video track occurred earlier (*visual lead*) or later (*auditory lead*) than in the original stimuli. This created 23 speech stimuli and 23 nonspeech stimuli, each set with SOAs ranging from −440 ms to +440 ms. The negative SOAs reflect an auditory lead whereas the positive SOAs reflect a visual lead.

In separate speech and nonspeech simultaneity judgment conditions, participants were asked to indicate as quickly and accurately as possible by button press whether the auditory and the visual components of the audiovisual events were in synchrony or not. Participants completed the nonspeech condition in their first test session and the speech condition in the second session. A total of eight blocks was presented in each condition. Each block consisted of 23 stimuli (22 asynchronous and one synchronous), shown in random order. A total of 184 trials was presented per condition. For both speech and nonspeech conditions, we report the percentage of synchronous responses.

McGurk Identification Task

The same stimuli (with the same SOAs) as in the speech condition of the simultaneity judgment task were presented. As before, white noise was added to these stimuli (at −16 dB SNR). The number of trials and blocks (eight blocks, each consisting of 23 stimuli) was the same as in the speech condition of the simultaneity judgment task. In the identification task, the participants were asked to indicate by button press what they had perceived (/aka/, /apa/, or /ata/). We report visually based (/k/), auditorily based (/p/), and fusion (/t/) response rates.

Phonetic Categorization Task

Participants were presented with steps from an audiovisual continuum between the Dutch nonwords /soːp/ and /soːt/. These stimuli were taken from van der Zande, Jesse, and Cutler (2013). A male native speaker of Dutch had been videorecorded with a Sony DCR-HC1000E camera and audiorecorded with two Sennheiser microphones. Videos showed the speaker's head and the top of his shoulders. Videos were digitized as uncompressed 720 × 576 .avi files in PAL format. The audio sampling rate was 44.1 kHz. A 21-step, auditory-only continuum and a 21-step visual-only continuum were created (see van der Zande et al., 2013, for details). Seven auditory steps and seven visual steps were selected and combined orthogonally for a pilot. Eighteen undergraduate students not involved in the main experiment participated in the pilot. Participants were instructed to look at and listen to the speaker and to indicate what the speaker had said (*soop* or *soot*) as quickly and accurately as possible. Each block consisted of 49 audiovisual stimuli presented in random order. A total of 10 experimental blocks was presented. On the basis of the pilot results, five audio steps (Step 1: 19% /p/ responses; Step 8: 34%; Step 10: 55%; Step 12: 61%; Step 21: 82%) and five visual steps (Step 0: 16% /p/ responses; Step 35: 33%; Step 40: 47%; Step 50: 68%; Step 100: 85%) were selected for the main experiment. From here on, we refer to the auditory and visual steps as Steps 1, 2, 3, 4, and 5, respectively. Each auditory step was combined with each visual step, resulting in a total of 25 videos. These stimuli had no noise added. Participants were asked to indicate by button press, as quickly and accurately as possible, whether the speaker had said *soop* or *soot*. Each block consisted of 25 audiovisual stimuli presented in random order. A total of eight experimental blocks was presented, resulting in a total of 200 trials. The mean percentage of /p/ responses across the combined steps of the auditory and the visual continuum are reported.

General Procedure

Informed consent was obtained from all participants of the study. All procedures performed in the present study were in accordance with the ethical standards of Radboud University.

Participants were tested in two separate sessions in order to avoid fatigue and to reduce possible influences between the experimental tasks. During the first session, participants completed the following tasks (in this order): hearing screening, reading, phonetic categorization, speechreading, McGurk identification, matrix reasoning, and the nonspeech condition of the simultaneity judgment task, as well as some additional tasks to be reported elsewhere. The speech condition of the simultaneity judgment task was completed during the second session together with several other tasks to be reported elsewhere.

The experimental tasks were controlled by Presentation software (Version 16.5, www.neurobs.com). Visual materials were displayed on a CRT monitor (Iiyama vision master pro451, 19-in. screen). The refresh rate of the monitor was set to 75 Hz (at 1280 × 1024 resolution), a multiple of the video's frame rate, to guarantee temporally accurate presentation of the stimuli. The audio was presented via Sennheiser headphones (Model HD 25 SP) at a fixed comfortable listening level (60 dB).

All four experimental tasks had the same presentation sequence: (a) a 50-ms black screen; (b) a fixation cross, presented for 250 ms; (c) a 200-ms black screen; and (d) the stimulus presentation. The videos were played in the center of the screen. Each video (in all tasks) lasted 2 s and was always played completely. After stimulus offset, the response options were presented on the screen, and the participants were asked to report their response by pressing one of the response buttons. If a response was not given within 5 s, the next trial was presented. A practice block always preceded experimental blocks to familiarize the participants with the procedure. Practice consisted of eight trials, except for the phonetic categorization task with five practice trials. Feedback on the procedure (i.e., how and when to give a response) was given only on practice trials.

Results

Reading and Cognitive Measures

Table 1 shows a summary of the included participants' performance in the reading tasks and in the other cognitive tasks. The number of errors made on the reading task correlated positively with the time taken to complete it ($r = .69$, $p < .001$). Two-sample independent-means *t* tests were used to test for group differences. In cases in which the assumption of the homogeneity of variances was violated, Welch corrections were applied to adjust the degrees of freedom. The statistical analyses confirmed that typical readers and readers with dyslexia differed significantly in reading accuracy and in reading speed. The groups did not differ in nonverbal cognitive ability or in their ability to speechread.

Simultaneity Judgment Task

Figure 1 shows the average percentage of responses judged as occurring simultaneously or in synchrony (referred to as *synchronous responses* from here on) for the speech and nonspeech stimuli at each SOA for the typical readers and the readers with dyslexia. This figure suggests that for both speech and nonspeech stimuli, readers with dyslexia perceived auditory and visual information as synchronous over a wider window than their controls. In addition, the differences between groups appear to be more pronounced for the visual leads (positive SOAs) than for the auditory leads (negative SOAs).

Mixed-effects models were implemented separately to analyze the data collected for auditory (negative SOAs) and visual leads (positive SOAs) in the speech and nonspeech conditions, using the lmer function in the lme4 package (Bates, Maechler, Bolker, & Walker, 2014) in R (Version 3.1.2, R Core Team, 2014). Type of answer (synchronous, asynchronous) was the binomial numeric dependent variable (asynchronous response = 0, synchronous response = 1). Group (typical readers = −0.5, readers with dyslexia = 0.5) was a contrast-coded fixed factor, and SOA was a scaled numeric fixed factor. To evaluate an effect of type of lead, we also report results from models containing type of lead as a contrast-coded fixed factor (auditory lead = −0.5, visual lead = 0.5). For these models, negative and positive SOAs were treated as equivalent (i.e., the magnitude of the SOA relative to the synchronous stimulus was analyzed, but the sign of the SOA was ignored). For all models, subjects were added as a random factor, along with by-subject slope adjustments for SOA (Barr, Levy, Scheepers, & Tily, 2013). Models were fit using the maximum likelihood criterion. *P* values were estimated using Satterthwaite approximations.

Speech Stimuli

For speech stimuli, readers with dyslexia gave more synchronous responses than typical readers, both for auditory lead ($\beta = .03$, $SE = 0.009$, $p < .01$) and for visual lead ($\beta = .07$, $SE = 0.009$, $p < .00001$). Likewise, SOA had a significant effect for both auditory ($\beta = .26$, $SE = 0.01$, $p < .00001$) and visual lead ($\beta = -.28$, $SE = 0.009$, $p < .00001$), with participants' responses changing across SOA in both parts of the continuum. The interaction between group and SOA was significant for visual lead ($\beta = .07$, $SE = 0.02$, $p < .001$). The change with SOA was larger for the readers with dyslexia than for the typical readers, indicating a wider temporal window for readers with dyslexia. This effect was only marginally significant for auditory lead ($\beta = -.04$, $SE = 0.02$, $p = .09$). We further combined the auditory and the visual lead portions to evaluate the effects of type of lead. Type of lead was not significant and did not contribute to any interactions (all *p*s > .05).

Nonspeech Stimuli

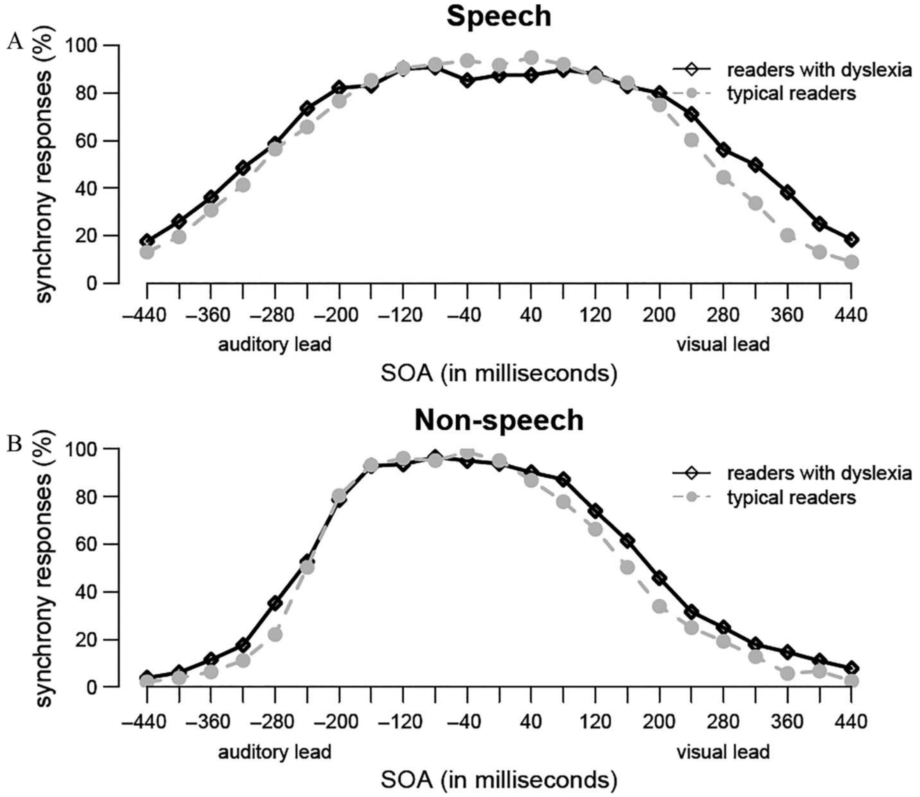
For nonspeech stimuli, readers with dyslexia gave more synchronous responses than typical readers for auditory lead ($\beta = .02$, $SE = 0.008$, $p < .01$) and for visual lead ($\beta = .07$, $SE = 0.009$, $p < .00001$). Again, responses changed across SOAs for auditory lead ($\beta = .37$, $SE = 0.006$, $p < .00001$) and did so differently by group ($\beta = -.02$, $SE = 0.01$, $p < .05$), suggesting a wider time window for readers with dyslexia than for typical readers. Responses also changed across SOAs for visual lead ($\beta = -.28$, $SE = 0.009$, $p < .00001$), but these changes were independent of group ($p > .05$). To examine the effects of type of lead, we also collapsed these data across SOA. Unlike for speech events, the type of lead had an effect on simultaneity perception for

Table 1. Average performance of typical readers and readers with dyslexia on the reading and cognitive measures.

Measure	Typical readers (*n* = 39)	Readers with dyslexia (*n* = 51)	*t* test	*p*	Cohen's *d*
Reading accuracy (number of errors)	5.36 (2.50)	19.18 (10.39)	*t*(57.41) = −9.16	< .00001	1.76
Reading speed (in seconds)	232.05 (16.07)	309.75 (45.81)	*t*(65.16) = −11.24	< .00001	2.15
Nonverbal cognitive ability (standardized score)	9.97 (2.54)	10.45 (2.23)	*t*(88) = −0.96	.35	0.20
Speechreading accuracy (proportion of correct answers)	0.40 (0.08)	0.38 (0.08)	*t*(88) = 1.24	.22	0.26

Note. Standard deviations are reported in parentheses.

Figure 1. Synchrony responses by stimulus onset asynchrony (SOA) and group for audiovisual speech (A) and nonspeech (B) stimuli.



nonspeech events ($\beta = -.13$, $SE = 0.02$, $p < .00001$). Group effects were again observed ($\beta = .05$, $SE = 0.006$, $p < .00001$) and were independent of type of lead. Responses changed across SOA ($\beta = -.33$, $SE = 0.006$, $p < .00001$), but this degree of change in slope was different depending on the type of lead ($\beta = .08$, $SE = 0.01$, $p < .00001$). As with the speech stimuli, however, there was no three-way interaction of SOA, type of lead, and group.

Speech Versus Nonspeech Stimuli

The proportion of synchronous responses given in the speech and nonspeech conditions was significantly correlated ($r = .72$, $p < .001$). We further tested if there were differences in the width of the windows for speech and nonspeech stimuli. A mixed-effects model was implemented. Type of answer (synchronous, asynchronous) was the binomial numeric dependent variable (asynchronous response = 0, synchronous response = 1). Group (typical readers = −0.5, readers with dyslexia = 0.5) and type of stimulus (speech = −0.5, nonspeech = 0.5) were contrast-coded fixed factors. SOA was a scaled numeric fixed factor. This analysis showed a decrease in synchronous responses with larger SOAs ($\beta = -.30$, $SE = 0.01$, $p < .00001$). Such a decrease was steeper for nonspeech than for speech stimuli ($\beta = -.06$, $SE = 0.01$, $p < .00001$). A three-way interaction among group, SOA, and type of stimulus ($\beta = -.04$, $SE = 0.02$, $p < .01$) revealed that the steeper decrease for nonspeech compared with speech was more profound for readers with dyslexia than for typical readers.

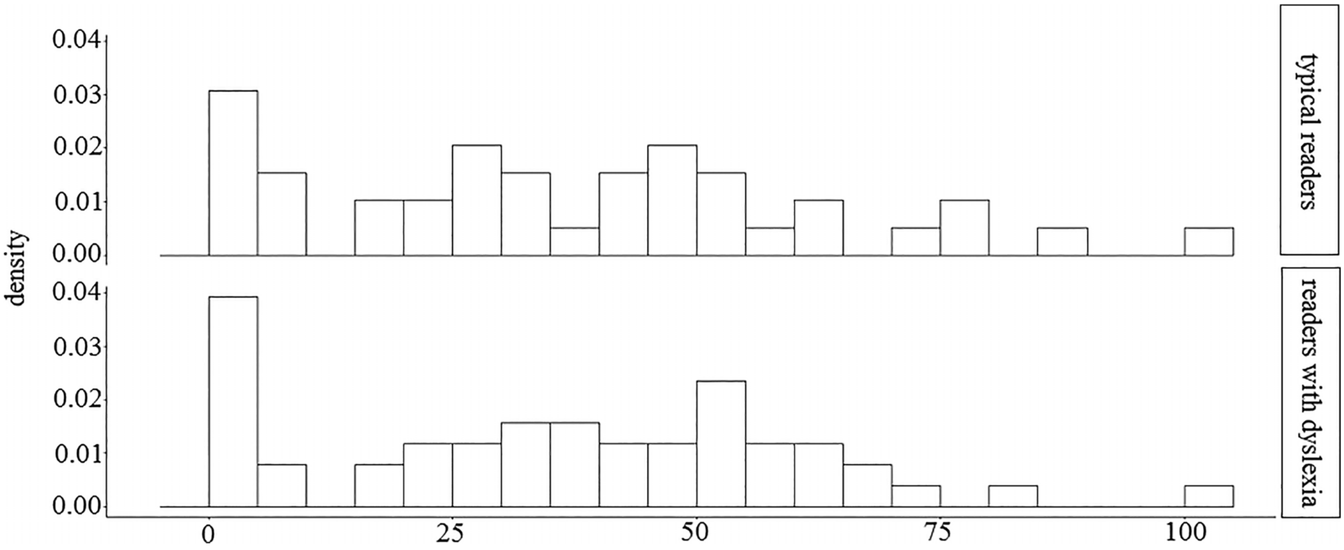
In summary, readers with dyslexia gave more synchronous responses than typical readers for speech and nonspeech stimuli. These group differences were observed both when the auditory portion of the stimuli was earlier in time and when the visual portion was earlier in time. The changes in synchronous responses across the speech and nonspeech continua were also different across groups, indicating a wider temporal window of perceived simultaneity for readers with dyslexia compared with typical readers.

McGurk Identification Task

Figure 2 shows the distribution of fusion responses per participant and per group. Figure 3 shows the mean response rates for readers with dyslexia and typical readers to McGurk stimuli across different SOAs. Response rates are plotted separately by group for visually based /k/ responses, auditorily based /p/ responses, and fusion /t/ responses. The results shown in this figure suggest that there are no group differences here for any type of response. The response distribution changes, however, as expected, across SOAs, indicating a larger visual influence for more synchronous presentations.

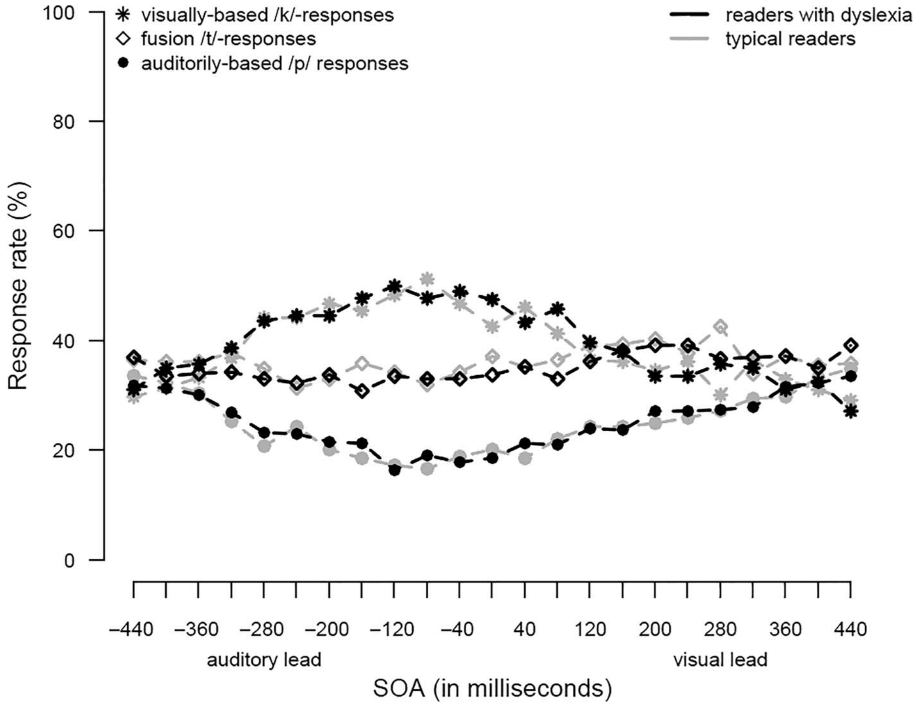
Mixed-effects models were used to analyze the data, using the same modeling approach as described above. However, for these analyses we did not separate the analyses

Figure 2. Distribution of fusion rates per participant and group. Each point represents one participant.



by lead type. We first analyzed the influence of group and SOA on auditory-based responses (i.e., /p/ responses). For this analysis, we created a binomial numeric dependent variable by coding /p/ responses as one and all other responses as zero. This analyses would hence code all visually influenced responses as 0, no matter whether or not they led to a fusion. For completeness and in a similar fashion, we analyzed effects on fusion responses (/t/ responses = 1) and on visually based responses (/k/ responses = 1). Results showed that all response types changed across SOAs (visual-based /k/ responses: $\beta = -.02$, $SE = 0.004$, p <.00001; fusion responses: $\beta = .01$, $SE = 0.04$, $p < .01$; auditory-based /p/ responses: $\beta = .01$, $SE = 0.003$, $p < .001$). Group had no main effect and did not interact with SOA ($p > .05$).

Figure 3. Response rates by groups across stimulus onset asynchrony (SOA).



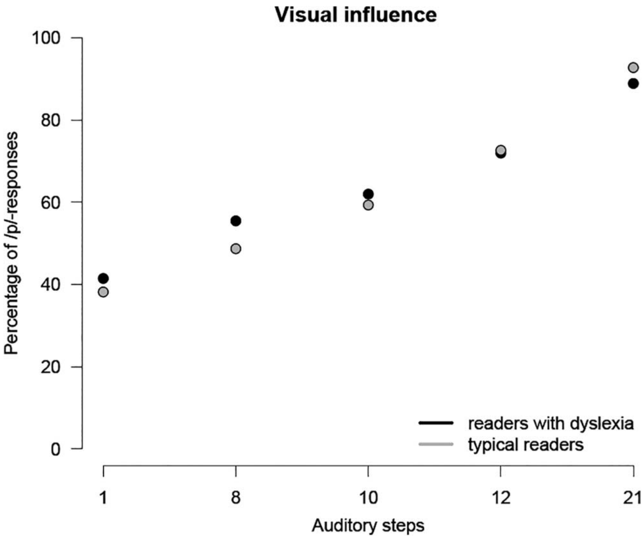
In summary, no differences were found between readers with dyslexia and typical readers for any type of response: auditorily based, visually based, and fusion responses. It is more important to note that changes in response rates across the SOAs were similar in both groups, suggesting a similarly sized time window of integration for adults with and without dyslexia.

Phonetic Categorization Task

Figure 4 shows each group's mean percentage of /p/ responses for each step on the auditory /t/–/p/ continuum, crossed with steps of the visual /t/–/p/ continuum. This figure suggests that visual information has an influence on the categorization of the auditory continuum but that this influence is similar across groups. In order to illustrate this better, we calculated the difference between the mean percentage of /p/ responses to the most /p/-like visual step minus the mean percentage of /p/ responses to the least /p/-like visual step. To account for differences in proximity to ceiling level performance—that is, for the amount of possible improvement—this difference was divided by 100 minus the mean percentage of /p/ responses to the most /p/-like visual step. The mean normalized benefit for each group at each step of the auditory continuum is plotted in Figure 5. The data depicted in this figure again suggest that both groups show a similarly large visual influence on their auditory categorizations.

Mixed-effects models were used for the data analyses, similar to what was described earlier. Type of answer (1 = /p/, 0 = /t/) was treated as a binomial numeric dependent variable. Group (typical readers = −0.5, readers with dyslexia = 0.5) was included in the models as a contrast-coded, fixed effect and auditory and visual steps as scaled, numeric fixed effects. Subjects and by-subject slope adjustments for auditory and visual steps were added as random effects. Group had no effect on categorizations and did not interact with any other factor ($p > .05$). More /p/ responses were given when presented with more /p/-like steps on the auditory ($\beta = .25$, $SE = 0.008$, $p < .00001$) and the visual continuum ($\beta = .16$, $SE = 0.01$, $p < .00001$). The interaction between auditory and visual steps was also significant ($\beta = -.02$, $SE = 0.004$, $p < .00001$). In summary, readers with dyslexia and typical readers did not differ in the visual influence on auditory perception. There were no significant correlations between tasks (all ps > .05).

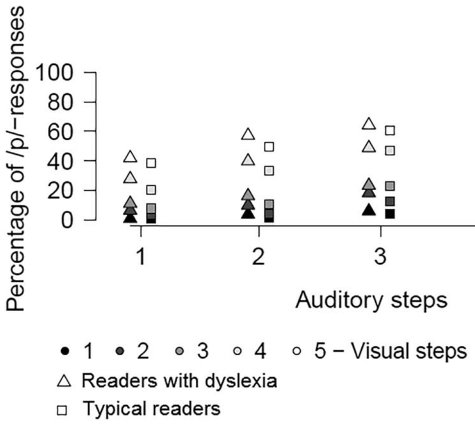
Figure 5. Mean change in percentage of /p/ responses between the most and least /p/-like steps on the visual continuum. This measure was calculated for each step of the auditory continuum for readers with dyslexia and typical readers and has been normalized on the basis of the auditory performance in the most /p/-like visual condition.



Discussion

The aim of the present study was to test if an audiovisual deficit was present in adults with developmental dyslexia. To be more specific, we determined if adult typical

Figure 4. Mean percentage of /p/ responses across the combined steps of an auditory and visual continuum for readers with dyslexia and typical readers (ranging from 1 = *less /p/-like* to 5 = *more /p/-like*).



readers and readers with dyslexia differed (a) in the time window over which auditory and visual speech and nonspeech events are perceived as occurring simultaneously, (b) in the temporal window of integration for audiovisual speech, and (c) in the extent to which their audiovisual perception of phonetic categories is influenced by information from the visual modality.

First, we showed that readers with dyslexia and typical readers differed in their audiovisual temporal sensitivity. Readers with dyslexia gave more synchronous responses to asynchronous stimuli than the typical readers for both speech and nonspeech stimuli. Furthermore, the change in response rates across SOAs differed by group, indicating that readers with dyslexia had a wider temporal window of perceived synchrony than typical readers. The differences observed between typical readers and readers with dyslexia in audiovisual temporal sensitivity for speech and nonspeech are in line with previous evidence of an altered temporal profile of audiovisual temporal perception in dyslexia for nonspeech events (Hairston et al., 2005). In addition, this result fits with earlier suggestions of an auditory temporal processing deficit in dyslexia (Tallal, 1984; for a review of the literature, see Farmer & Klein, 1995). It is important to note that we added to Hairston et al.'s (2005) results by showing differences both in speech and in nonspeech events. This suggests that the audiovisual deficit in dyslexia is broad rather than specific to letter–speech sound associations or to nonspeech events. In addition, both groups showed narrower temporal windows for the nonspeech when compared with the speech events, which concurs with previous findings in typical adult readers (e.g., Vatakis & Spence, 2006). Hence, although readers with dyslexia showed a deficit in audiovisual temporal perception for both speech and nonspeech events, they still showed a narrower window for stimuli that were less complex (and more prominently than the typical readers). This cross-modal temporal deficit—reflected here as wider windows during which asynchronous events are perceived as synchronous —could result in impaired reading. Given that adequate associations between graphemes and phonemes occur in narrow time windows (Froyen et al., 2008), a cross-modal deficit that results in the widening of audiovisual temporal windows could impair the development of such associations and, as a consequence, reading—that is, it could hamper the formation of adequate representations, creating ambiguity in the correspondences between graphemes and phonemes (Wallace & Stevenson, 2014). This could result in reductions in the speed with which printed representations are decoded (Hairston et al., 2005) and lead to more errors in the accurate pairing of orthography and speech sounds (Hahn, Foxe, & Molholm, 2014). As an alternative, it is possible that readers with dyslexia experience difficulties in the uptake of information and extend their temporal windows to compensate for the difficulties in sensory processing. Such a compensatory mechanism has been previously shown in older adults (Diederich et al., 2008; Laurienti et al., 2006). In summary, we have demonstrated the existence of a general audiovisual temporal deficit in dyslexia, restricted neither to reading nor to language. Both this deficit and reading impairment in dyslexia may be the effect of a third (currently unknown) factor.

Second, we observed no group differences in the time window of audiovisual integration of information about stop consonants. The two groups performed similarly with regard to the rate of auditorily and visually based responses as well as the rate of fusion responses in our McGurk identification task. The rate of visually based responses peaked with more synchrony, and the rate of fusion and of auditory-based responses declined with more synchronous stimuli. Overall, participants reported more visually based responses than fusion responses and auditory-based responses. Auditory-based responses had the lowest overall rate probably because the informativeness of auditory information was lowered by the added noise. The lower rate of auditory-based responses does not seem to be due to the instructions to report what is perceived rather than what is heard. In a separate pilot study ($N = 14$) we obtained similar results when we asked typical readers to report what they heard (instead of perceived). The rate of visual-based responses also exceeded the rate of fusion responses possibly because the visually presented /aka/ was clearly recognizable and thus did not support the /ata/ interpretation (see Tiippana, 2014, for a similar argument and, e.g., Andersen, Tiippana, Laarni, Kojo, & Sams, 2009; Saalasti et al., 2012, for similar patterns).

In combination, these two sets of results showed that readers with dyslexia and typical readers differed in terms of audiovisual temporal sensitivity but showed similar temporal windows of integration. This points to a dissociation between the judgment of synchrony and the attainment of perceptual integration (Conrey & Pisoni, 2006; Soto-Faraco & Alsius, 2007, 2009; van Wassenhove et al., 2007), which is in accordance with evidence showing that different brain networks are involved in the detection of audiovisual simultaneity and in audiovisual integration (Miller & D'Esposito, 2005). As an alternative, this dissociation could relate to the nature of the tasks and to the processes considered in the present study. We showed that readers with dyslexia performed more poorly than typical readers when making explicit judgments about the temporal synchrony of the events. However, no differences were observed when the groups were making implicit judgments about that same synchrony when determining phonetic identity, using identical stimuli. It is interesting to note that reading requires conscious reflection about letter–sound correspondences and their synchrony—that is, a percept in one modality has to be mapped onto another modality— but there is no single representation for a letter–sound correspondence. In audiovisual speech, however, information from two modalities is integrated into a single overall percept. Hence, synchrony is used implicitly in audiovisual speech integration but explicitly in reading. It is thus possible that a core aspect of the role of an audiovisual deficit in the acquisition of letter–sound correspondences in dyslexia lies in the ability to make explicit judgments about timing. An explanation along these lines would also account for the absence of differences between readers with dyslexia and typical readers in audiovisual speech perception. Furthermore, it is interesting to note that other hypotheses about the nature of dyslexia also suggest that the deficit may lie in conscious reflective processes, such as the hypothesis that readers with dyslexia have problems with accessing (otherwise unimpaired) phonological representations (Boets et al., 2013; Ramus & Szenkovits, 2008). Further research is needed to clarify the plausibility of these two explanations (i.e., that on the basis of distinct mechanisms for simultaneity and perceptual judgments vs. that on the basis of the ability to make explicit judgments). Electrophysiological and neuroimaging studies requiring both explicit and implicit judgments (and tapping into both time windows) may shed some light on possibly distinctive mechanisms underlying each of these tasks.

Our third finding was that there were no group differences between readers with dyslexia and typical readers in audiovisual speech perception abilities. In the phonetic categorization task, both groups gave more /p/ responses when presented with more /p/-like steps on the auditory and visual continua. It is more important to note that the change in /p/ responses for auditory steps as a function of visual step was the same across groups. In the McGurk identification task, no differences were found between groups in terms of their response rates. This absence of differences between readers with dyslexia and typical readers is in line with the studies reporting intact audiovisual speech perception in dyslexia (Baart et al., 2012; Campbell et al., 1997; de Gelder and Vroomen, 1998; Groen & Jesse, 2013). This result is, however, at odds with studies showing fewer fusion responses in children (Hayes et al., 2003) and adults (Norrix et al., 2006) with learning disabilities. It is important to note that we tested adults diagnosed with developmental dyslexia whereas both Hayes et al. (2003) and Norrix et al. (2006) tested individuals with learning disabilities. Although dyslexia is the most frequent learning disability, learning disabilities may reflect arithmetic, handwriting, and/or spelling problems (Shaywitz, Fletcher, & Shaywitz, 1995). The multidimensional nature of learning disabilities and the possible differences between the disabilities included in it may explain the differences between our results and those of Hayes et al. and Norrix et al. As an alternative, it may be the case that speech processing is too easy a task for adult readers to perform: Speech is encountered since infancy and on a very regular basis, and the learning of the causal relationships between sounds and mouth gestures is implicit—opposite characteristics to the reading process. In addition, it may be that the tasks were not sufficiently difficult to reveal difficulties in readers with dyslexia. Deficits in speech perception might only come to light under more challenging conditions. Indeed, Hayes et al. reported differences between learning-disabled and normal-learning children but only when the stimuli were presented with a high level of noise. Moreover, Hazan, Messaoud-Galusi, and Rosen (2013) showed that children with dyslexia exhibited difficulties in speech-in-noise perception but only when the speaker's intonation was variable or when the listeners were under greater memory and cognitive load as in discrimination tasks. It is also possible that deficits that could emerge in the perception of words or sentences may have gone undetected in the current task with isolated nonsense syllables (e.g., Grant & Seitz, 1998; Sommers, Tye-Murray, & Spehar, 2005). A different possibility is that differences between typical readers and readers with dyslexia are not easily observable behaviorally. Indeed, Widmann et al. (2012) observed large and significant differences between typically developing children and children with dyslexia on the neurophysiological level in a symbol-to-sound matching task, and at the same time, this resulted in only slightly worse performance in the readers with dyslexia on the behavioral outcomes of this processing. In the behavioral experiment conducted by Widmann et al. (2012) and in the present study, individual and group differences in perception may have been diminished by postperceptual compensatory strategies.

In summary, we have shown no differences between typical readers and readers with dyslexia in their perception of audiovisual speech. We hypothesize that, although differences in speech perception may exist between the two groups during childhood, those differences cease to exist in remediated readers with dyslexia, possibly due to the development of compensatory strategies, and to accumulated experience with speech processing.

Conclusion

Reading is an audiovisual process that requires the learning and the automatization of systematic links between graphemes and phonemes. It is thus plausible to assume that reading impairment in developmental dyslexia may reflect an audiovisual deficit. Our results are in line with such an assumption, showing that adult readers with dyslexia have a wider time window of perceived audiovisual synchrony than typical readers, for both speech and nonspeech stimuli. No difference was found, however, in the size of the temporal window of integration and in audiovisual speech perception. This dissociation is consistent with an audiovisual system that makes use of distinct mechanisms to accomplish different tasks. As an alternative, the audiovisual deficit in readers with dyslexia might reflect problems with making explicit simultaneity judgments. Either way, these results point toward the presence of a domain-general audiovisual temporal processing deficit in developmental dyslexia.

Acknowledgments

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