Poor anchoring limits dyslexics' perceptual, memory, and reading skills

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A R T I C L E   I N F O

Article history:
Received 3 December 2011
Accepted in revised form 13 April 2012
Accepted 15 April 2012

Keywords:
Dyslexia
Anchoring
Auditory perception
Frequency discrimination
Learning
Non-words
Audition

A B S T R A C T

The basic deficits underlying the severe and persistent reading difficulties in dyslexia are still highly debated. One of the major topics of debate is whether these deficits are language specific, or affect both verbal and non-verbal stimuli. Recently, Ahissar and colleagues proposed the “anchoring-deficit hypothesis” (Ahissar, Lubin, Putter-Katz, & Banai, 2006), which suggests that dyslexics have a general difficulty in automatic extraction of stimulus regularities from auditory inputs. This hypothesis explained a broad range of dyslexics’ verbal and non-verbal difficulties. However, it was not directly tested in the context of reading and verbal memory, which poses the main stumbling blocks to dyslexics. Here we assessed the abilities of adult dyslexics to efficiently benefit from (“anchor to”) regularities embedded in repeated tones, orally presented syllables, and written words. We also compared dyslexics’ performance to that of individuals with attention disorder (ADHD), but no reading disability. We found an anchoring effect in all groups: all gained from stimulus repetition. However, in line with the anchoring-deficit hypothesis, controls and ADHD participants showed a significantly larger anchoring effect in all tasks. This study is the first that directly shows that the same domain-general deficit, poor anchoring, characterizes dyslexics’ performance in perceptual, working memory and reading tasks.

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1. Introduction

Developmental dyslexia is a specific learning disability characterized by persistent difficulties in the acquisition of adequate reading skills (Snowling, 2000). These difficulties are manifested in poorer letter-to-sound decoding accuracy and rate, and typically concur with poor verbal working memory (Snowling, 2000). Although it is one of the most prevalent developmental disorders, estimated at 3–10% of the population, the cognitive deficits that underlie dyslexics’ difficulties are still under dispute (Ramus, 2003).

According to the dominant theoretical framework, the phonological deficit theory (Snowling, 1998), dyslexics’ poor decoding abilities result from a specific deficit, restricted to a particular aspect of the language domain, phonology. The phonological hypothesis attributes poor decoding to impaired awareness of, access to, or perhaps even poor representations of basic speech sounds (Bradley & Bryant, 1983). It also attributes dyslexics’ well-documented deficit in verbal working memory to poor access to phonological representations (De Jong, 1998; Isaki, Spaulding, & Plante, 2008). This proposed link between slow access to phonological representations and impaired verbal memory capacity is based on Baddeley’s model of working memory (Baddeley, 2003), according to which an activated item is retained in working memory only for 2–3 s unless re-activated by rehearsal. Therefore, slow access reduces working memory span.

However, it has also been suggested that dyslexics’ core deficit is poor working memory and their poor performance in phonological awareness tasks stems from this deficit (Gathercole & Baddeley, 1990). Since phonological awareness tasks typically require retention and manipulation of sequences of speech sounds, a difficulty in these processes is expected to impede performance even when phonological awareness itself is adequate (Landerl & Wimmer, 2000).

A key tenet of the phonological deficit hypothesis is that it assumes a domain specific impairment. However, reading-impaired individuals tend to have broader cognitive difficulties, which include other linguistic abilities (Bishop & Snowling, 2004), attentional skills (Kadesjö & Gillberg, 2001), and poorer performance in a range of simple visual (Eden et al., 1996; Ramus et al., 2003; Talcott, Hansen, Assoku, & Stein, 2000; Witton et al., 1998) and auditory (Ahissar, Protopapas, Reid, & Merzenich, 2000; Amitay, Ahissar, & Nelken, 2002; Helenius, Uutela, & Hari, 1999; Tallal, 1980; Tallal & Piercy, 1974) tasks. The phonological deficit hypothesis thus needs to assume that this concurrence has no functional relevance (Dawes et al., 2009; Rosen, 2003). This is a strong assumption given that dyslexics’ degrees of impairment are correlated across perceptual and cognitive domains (Ahissar et al., 2006; Ahissar et al., 2000; Q6)

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0028-3932/– see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.neuropsychologia.2012.04.014

Several researchers have proposed alternative accounts, which attributed dyslexics’ reading deficits to non-linguistic impairments (for a review see Démonet, Taylor, &Chaix, 2004). A prominent early hypothesis by Tallal (1980) suggested that dyslexics’ deficits result from impaired processing of brief sounds (20–30 Hz), which leads to poor perception of speech sounds, particularly consonants, which in turn leads to the development of fuzzier phonological representations. Its predictions were testively tested, but with mixed results (e.g. Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; Ramus et al., 2003 versus Groth, Lachmann, Riecker, Muthmann, & Steinkrull, 2009; Lehongre, Ramus, Villiermet, Schwartz, & Giraud, 2011). More recently it has been suggested that temporal processing at slower rates, which are important for speech segmentation at the syllabic level (Goswami et al., 2002), and for tracking the envelope of sentence amplitude modulation (4–16 Hz; Ahissar et al., 2001; Goswami, 2011; Goswami et al., 2010) is impaired in dyslexia. At its lower frequency range (~2 Hz), the revised temporal hypothesis relates to temporal scales that characterize attentional processes required for perceptual integration and explicit object identification (see discussion in Ramus & Ahissar, 2012). Indeed, several researchers have argued that impaired spatio-temporal attentional abilities are the source of dyslexics’ difficulties (e.g. Hari & Renvall, 2001; Vidyasagar & Panner, 1999; Facetti et al., 2010). A key finding supporting this attentional hypothesis is that when brief stimuli are presented in a rapid sequence (RSP), dyslexics detect the presentation of an anticipated item adequately, but require a longer time interval (~0.5 s) than control participants before they can identify a subsequently presented stimulus (Hari, Valta, & Uutela, 1999; Roach & Hogben, 2007). Although these various hypotheses relate to quite different time scales, they are often grouped together in the “magnocellular hypothesis” (Livingstone, Rosen, Drislane, & Galaburda, 1991; Stein & Watan, 1997), since it has been speculated that these behavioral deficits reflect an impairment in the dorsal pathways, either at the input level – which mainly consists of the magnocellular layers of the thalamus (e.g. Galaburda & Livingstone, 1993) – or at a later stage (we should note that the question of specific visual deficits, e.g. spatial attention in dyslexia (e.g. Moores, Cassim, & Talcott, 2011) is beyond the scope of the present paper).

More recently, domain general formulations have focused on dyslexics’ increased noise sensitivity (internal (Amitay, Ahissar et al., 2002) and external: visual (Sperling, Lu, Manis, & Seidenberg, 2005, 2006) and auditory (Wible, Nico, & Kraus, 2002; Ziegler, Pech-George, George, & Lorenzi, 2009; Ziegler, Pech-George, George, Alario, & Lorenzi, 2005)). Increased noise sensitivity may be viewed as a quantitative formulation of a hypothesis of poor-selective-attention. However, neither formulation specifies the mechanisms for implementing this selection. Ahissar (2007); (Ahissar et al., 2006) proposed the “anchoring deficit hypothesis”, which suggests a specific mechanism that accounts for dyslexics’ poor selection of signal from noise, and specifies the conditions under which this difficulty is expected to appear. This hypothesis (Ahissar, 2007) posits that dyslexics’ detection of regularities in sound sequences is inefficient. The general population rapidly utilizes simple statistics (e.g. repeated stimuli and sequences of stimuli) that characterize every stimulation context (Nahum, Daikin, Lubin, Cohen, & Ahissar, 2010). Ahissar et al. (2006) termed this quick tracking mechanism “anchoring” (following the terminology of pioneering psychoacoustic studies, Harris, 1948), and claimed that dyslexics’ anchoring mechanisms are impaired. This hypothesis was based on their findings that individuals with reading and additional learning difficulties (D-LD) have an anchoring deficit in simple 2-tone frequency discrimination tasks and in the perception of speech in noise (see also the results of Chandrasekaran, Hornickel, Skoe, Nicol, & Kraus, 2009; Nittrouer, Shume, & Lowenstein, 2011). They observed that teenaged D-LDs’ frequency discrimination is particularly poor compared to their adequately reading peers, when measured around a repeated reference tone. However, in the more difficult version of this task, which contains no stimulus repetition and yields substantially higher thresholds in the general population, D-LDs show no significant difficulties compared with their peers. Similarly, their identification of speech in noise is impaired when a small set of repeated words is used, but not when a large set of words is used with almost no word repetition. In both tasks, the conditions that did not provide anchoring benefits were the most difficult ones for controls. Yet, D-LDs’ performance was particularly impaired in the easier, more structured conditions, indicating that perceptual difficulty does not pose a bottleneck to their performance.

The conceptual strength of the anchoring deficit hypothesis is that it provides a mechanism, which accounts for a broad range of seemingly unrelated behavioral findings in a coherent manner (Ahissar, 2007). Moreover, it provides specific predictions regarding both the conditions that will be challenging to dyslexics and the conditions that will not be challenging (Banai & Ahissar, 2010; Ramus & Ahissar, 2012). Its main drawback, however, is similar to that of other domain general hypotheses. Namely, its direct applicability to dyslexics’ main difficulties, i.e. poor verbal memory and poor decoding of written script, was not tested. Another limitation of the theory is that it has never been shown to be specifically related to reading deficits, since it is based on studies of individuals with broader learning difficulties (D-LDs). An anchoring deficit may thus characterize general academic or perhaps attentional difficulties (Willburger & Landerl, 2010).

Yet another limitation of the anchoring hypothesis is that differences in anchoring abilities between dyslexic and control populations may be a result rather than a cause. The ability to detect regularities in auditory stimuli is probably related to musical aptitude and may improve with musical training (e.g. Forde, Winner, Norton, & Schlaug, 2008; Ho, Cheung, & Chan, 2003; Michely, Delhorne, Perrot, & Oxenham, 2006; Moreno et al., 2009). Moreover, musical training may generalize to detect speech regularities. For example, sub-cortical processing of speech regularities predicts both reading and musical aptitude in children (Strait, Hornickel, & Kraus, 2011). In adults, the degree of sub-cortical signal enhancement of predictable sound stimuli is correlated with the amount of musical education (Parbery-Clark, Strait, & Kraus, 2011). Although general education is often matched between groups of participants, musical training is not specifically addressed, and hence may not be matched. Given the conceptual link between music and speech perception, which is implied by the anchoring hypothesis and the experimental data supporting such links, one aim of this study was to assess whether different degrees of musical education can account for anchoring differences between groups.

The first aim of the current study was to verify that even academically high-achieving dyslexics have an anchoring deficit, as measured by frequency discrimination. The second aim was to assess whether this deficit is specific to dyslexia, rather than a general characteristic of an attention deficit, which tends to concur with dyslexia (Kadesjo & Gillberg, 2001; Snowling, 2000). To this end we assessed individuals with ADHD and no Dyslexia. The third aim was to verify that if dyslexics have an anchoring deficit this deficit is not simply a result of differences in musical education. The fourth aim was to assess whether an anchoring deficit also impairs dyslexics’ verbal working memory. The fifth was to assess whether it also limits their reading skills.

In line with the anchoring hypothesis, we found that anchoring abilities were consistently and specifically impaired in the
dyslexic group, limiting their perceptual, verbal memory and reading abilities.

2. Methods

2.1. Cognitive and phonological tests

1. General cognitive abilities were assessed with 2 subtests from the Hebrew version of the Wechsler Adult Intelligence Scale (WASI-H): Block Design for visuo-spatial reasoning abilities, and Digit Span for verbal working memory (Wechsler, 1997).

2. Phonological decoding—single pseudo-word and real-word reading—was assessed using two standard Hebrew lists designed by Deutsch and Benton (Deutsch & Benton, 1996). One list contains 24 punctuated Hebrew words and the other contains 24 punctuated pseudo-words; i.e. words with Hebrew morphology but no meaning. Both accuracy and rate were scored. Scores on word and pseudo-word reading were converted to z-scores based on population norms (http://elsc.huji.ac.il/ahissar/links)—choose Hebrew Reading Norms), and were combined to two phonological scores: reading rate, averaged across word and pseudo-words, and reading accuracy, which included only pseudo-words, since real words were read with nearly 100% accuracy by non-dyslexic participants.

3. Sustained attention was assessed with the CPT (Conner’s Continuous Performance Test, CPT-II, Conners, 2000), a standard computerized test. It produces a final report that contains a confidence index (between 0 and 100%) indicating the similarity of performance pattern to that of individuals with an attention deficit/hyperactivity disorder (ADHD). Scores below 40% are considered well within the normal range; scores above 60% are interpreted as an ADHD profile. This test was not used for diagnosis of ADHD (see next sub-section), but as an additional experimental measure of the sustained attention of our participants. Only 25 controls, 32 dyslexic participants, and 22 ADHD subjects completed this task.

4. Musical background was assessed based on questionnaires. Participants reported the amount of their formal musical education. Our binary criterion for “prior musical training” was formal musical education with a total instrument for at least one year.

2.2. Measures of anchoring abilities

Experiment 1: Auditory frequency discrimination (FD) tasks

Perceptual thresholds for auditory 2-tone frequency discrimination (FD) were measured using a two-alternative forced choice (2AFC) paradigm. In each trial, two 50 ms tones were presented with an inter-stimulus interval of 950 ms. After hearing both tones, participants had to decide which tone had the higher pitch (frequency) and to press the corresponding button. In each trial visual feedback was given. A happy face followed a correct response and a sad face followed an incorrect button press. The subsequent trial began 1 s after the participant’s response. Thresholds were assessed in blocks of 80 trials, using an adaptive 3-down 1-up staircase procedure, converging to 75.5% correct (Levitin, 1971). The step size (amount of change in % frequency difference between the tones) was decreased every four reversals from 4.5 to 2 to 1 to 0.1. One of the tones in a trial was chosen according to a specific protocol (described in the next paragraph), and the second was determined according to the staircase procedure. Discrimination thresholds (Just Noticeable Difference, JND) were calculated as the mean frequency difference in the last five reversals.

This task was conducted with the following three protocols (presented in the order of their assessment):

A. Reference-low (RL)—In this protocol one of the two tones in each trial was 1000 Hz. The other, non-reference tone was always higher. This is the standard protocol used in psychophysical measurements.

B. No reference (NR)—In each trial of this protocol one of the two tones was chosen randomly, with a uniform probability, from the range of 800 to 1200 Hz. The other tone was chosen subsequently as either higher or lower according to the same adaptive paradigm. NR and RL were both tested by Ahissar et al. (2006).

C. Reference 1st (R1)—In this protocol, the first tone of each trial was 1000 Hz. The second tone was either higher or lower, using the same adaptive paradigm. This protocol yields the largest anchoring effect and hence substantial low-level discrimination thresholds (Nahum et al., 2010). We therefore reasoned that poor anchoring would lead to relatively poor performance in this protocol, in spite of its being the easiest one.

All protocols are fully implemented in the open web site (http://papi.huji.ac.il) (for English click on ‘switch to English’ in the right upper corner).

Each participant performed two blocks of each protocol in the following order. Reference low (RL), no reference (NR) and reference 1st (R1). Each pair of blocks was separated by 10–15 min during which other tasks were performed. Although we administered two assessments for each condition we discuss only the first threshold since the focus of the present study is on the initial anchoring rather than learning effects in repeated assessments. Pilot studies showed that administering the reference containing condition prior to the NR condition did not improve thresholds in the latter. The dynamics between the first and the second assessments, which differed between protocols and groups, are presented in detail elsewhere of Oganian and Ahissar in preparation.

Since sensitivity to stimulus changes is scaled with its absolute level (Weber law), thresholds were power-transformed (logarithm) prior to all analyses. The transformed scores were normally distributed.

All stimuli were presented binaurally through Sennheiser HD-265 linear headphones using a TDT (Tucker Davis Technologies) System III signal generator controlled by in-house software in a sound-attenuated chamber in the lab. Tone intensity was 65 dB SPL.

Experiment 2: Verbal working memory—syllable span tasks

This paradigm was designed on the basis of the procedure for assessing forward Digit span in this WISE sub-test (Wechsler, 1997). Participants were presented with sequences of syllables of increasing length, and were requested to repeat the syllables in the presented order. Participants were presented with two sequences for each length, starting with two syllables; the task continued until the participant either failed in two sequences of the same length or reached the maximal sequence length of 8 syllables. The recorded syllable sequences were presented to participants through headphones at a comfortable volume, i.e., participants were allowed to adjust the level of the headphones during a first test trial (resulting in 70–75 dB SPL). Performance was evaluated as the number of correctly reproduced sequences (score) and the number of syllables in the last correctly reproduced sequence (span).

We used two different protocols:

A. No repetition (NR)—In this protocol, each syllable appeared only once during the whole test.

B. Repetition (REP)—In this protocol, sequences of increasing length were presented by adding, at the end of the last sequence (see Supplementary Material). Two different syllable sequences were presented for each sequence length. Thus, once introduced, every syllable kept its serial position.

The order of assessment of the REP and NR conditions was counter-balanced across participants.

Experiment 3: Single non-word (NW) reading task

This paradigm was designed on the basis of the RAN (Rapid Automatized Naming) procedure, where 5 different items are presented many times in 40–50 item lists. Participants are asked to name them as fast as possible (Denckla & Rudel, 1976; Wolf, Bowers, & Biddle, 2000). We adapted it to an oral reading task, composed of 5 different non-words (NWs), and recorded the reading session, which enabled us to track the reading rate of each word as a function of encounter number. The 5 NWs differed in length and in phonological regularity: 2 were very irregular, one of which was trisyllabic (/pītupēk/) and the other bisyllabic (/fls/), one had intermediate regularity (/metitla/) and two were regular trisyllabic NWs (/nimitas and /zakuka/). These levels of regularity were verified in a rank-order regularity questionnaire that was distributed to 10 naive students. They all ranked the 2 irregular words as least regular, and the 2 regular words as most regular. The 5 words were presented in a pseudo-random order, on 3 pages, each containing 20 words (thus each word was repeated at least 11 times). Each page was presented on an 18 in. computer screen in punctuated Hebrew script.

The different degrees of regularity were designed to assess the effect of word regularity on reading performance and its improvement. We reasoned that the impact of anchoring would be particularly crucial for the reading rate of the most irregular non-words, since initial reading would be based only on on-line phonological decoding (given no previously familiar phonotactics or morphology) but no meaning. Both accuracy and rate were scored. Scores on the other contains only pseudo-words, since real words were read with nearly 100% accuracy by non-dyslexic participants.

Scores above 60% are considered well within the normal range; scores above 60% are interpreted as an ADHD profile. This test was not used for diagnosis of ADHD (see next sub-section), but as an additional experimental measure of the sustained attention of our participants. Only 25 controls, 32 dyslexic participants, and 22 ADHD subjects completed this task.

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sake of clarity these two repetitions are referred to as Day 1 and Day 2 from here on. Due to the complicated structure of the stimuli, participants often made longer articulation breaks not only before they began reading a NW but also while reading it (e.g. /pultapek/), making a clear separation between preparation time (time to onset) and articulation time impossible. We therefore included the entire interval between one reading offset and the subsequent one as reading duration in the analyses of reading rates. The first item on each page was read much slower than the other NWs on the same page. This effect of page beginning was relatively fixed and similar in both groups (0.95 s on Day 1 and 0.9 s on Day 2). It was subtracted from the averages in Fig. 3 for presentation purposes. Statistical analyses of reading duration for single encounters were conducted with the original data. Ratios of reading duration were calculated excluding the first item of each page (first encounter with /pultapek/), 5th encounter with /fritos/, and 9th encounter with /nimitas/), which is a conservative approach in terms of our predictions. For the analysis of reading accuracy, accuracy was calculated as percentage of correctly read NWs (within a session) for irregular and regular NWs separately.

Order of assessment

Cognitive and phonological tests and Experiment 1 were administered in the first 3-h session. The second session contained Experiment 2 and the first repetition of Experiment 3. The second repetition of Experiment 3 took place in the third session (the two repetitions of Experiment 3 are referred to as Day 1 and Day 2 in the following). Each of these sessions lasted approximately half an hour. The time interval between participation in Experiment 1 (session 1) and Experiments 2–3 (sessions 2–3) ranged between several weeks and several months. Sessions 2 and 3 were administered between one and three days apart.

2.3. Participants

A hundred and thirty two students of the Hebrew University of Jerusalem participated in the study; 47 with a diagnosis of dyslexia (mean age 24.7 ± 3 years; 14 females), 52 control participants (24.3 ± 3.6 years; 17 females), and 33 with a diagnosis of ADHD (mean age 24.5 ± 3 years; 12 females). Only native Hebrew speakers with no history of hearing problems (verified by a quick hearing test) were included. All participants, with a diagnosis of ADHD and dyslexia, were recruited through advertisements at the Hebrew University, and through the University’s center for learning disabled students. The three groups of participants were matched for age and gender. All were students attending institutions of higher education (either the Hebrew University or Jerusalem’s Academy of Arts). All participants signed a written consent form describing the aims and the behavioral tasks of the study. Participants were reimbursed for their time according to standard hourly student rates.

All participants took part in Experiment 1. None of the ADHD participants was on medication during the experiment. All control and dyslexic participants of Experiment 1 were invited to take part in Experiments 2–3. Yet, only 27 of the control participants and 28 of the dyslexic participants agreed to return for these experiments. Participants with ADHD were not invited to participate in Experiments 2–3, since they showed no anchoring deficits in Experiment 1.

The current study was approved by the ethical committee of the Hebrew University of Jerusalem. All participants gave informed consent. All participants gave their written informed consent to participate in the study. The data of seven participants (3 controls, 3 dyslexics, and 1 with ADHD) were excluded on the basis of their phonological scores. Data of one additional ADHD participant were excluded, since his frequency discrimination scores were an extreme outlier (more than 10 SDs above his group’s average). Taken together, the data of 49 controls, 44 dyslexics, and 31 ADHD participants were included in the data analysis. None of the participants was on medication during the assessment of the experiment, even though some ADHD participants occasionally used Ritalin before exams.

The average cognitive and reading profile of the participants in Experiments 2 and 3 did not differ from that of the participants in Experiment 1.

3. Results

3.1. Cognitive and reading profiles

General, non-verbal reasoning skills, measured by the standard Block Design test, were similar across groups, and were above the average of the general population (Table 1). On the other hand, as expected (De Jong, 1998; Jeffries & Everatt, 2004), dyslexics’ verbal working memory scores, measured by Digit Span (see Table 1), were lower than the average of the general population and substantially lower than those of control and ADHD participants, t(123) = −5.82, p < 0.001. As expected (and verified by our selection criteria), dyslexics’ reading accuracy was significantly poorer than that of the other two groups, t(123) = 14.6, p < 0.001, whereas control and ADHD participants read with similar accuracy. Dyslexics’ reading rate was the slowest, t(123) = −7.95, p < 0.001, whereas ADHD participants were slower than controls, t(80) = −3.53, p < 0.001, but still significantly faster than dyslexics, t(75) = −4.7, p < 0.001. Thus, dyslexics’ reading was both highly inaccurate and very slow, whereas ADHD participants were accurate, yet slightly slower than Controls. None of the ADHD participants reported reading difficulties.

The average scores of controls in sustained attention (measured by CPT) matched the expected profile of the general population (< 40%; see Table 1). The average scores of the two other groups were significantly higher (i.e. between 40 and 60%; the “light” ADHD zone) and comparable, in line with previous reports (e.g. Ben-Yehudah & Ahissar, 2004) and with the well-documented high concurrence of ADHD and dyslexia (Snowling, 2000). Although average CPT scores were similar in the ADHD and dyslexic group, their distribution somewhat differed. All but two participants in the ADHD group scored above 40, whereas in the dyslexic group 14 of 35 participants had scores in the normal range. This similarity of the average CPT scores allowed us to assess whether difficulties in sustained attention, shared by both groups, are sufficient to induce anchoring difficulties in auditory

Please cite this article as: Oganian, Y., & Ahissar, M. Poor anchoring limits dyslexics’ perceptual, memory, and reading skills. Neuropsychologia (2012), http://dx.doi.org/10.1016/j.neuropsychologia.2012.04.014
tasks, which was one of the aims of Experiment 1. Due to their broad within-group distribution, we also calculated correlations between CPT scores and performance in other tasks.

3.2. Measures of anchoring abilities

Experiment 1: Frequency discrimination in Controls, Dyslexics and individuals with ADHD

The first aim of this experiment was to assess whether high academically achieving dyslexics are consistently poor frequency discrimination protocols that contain simple regularities (and hence allow to benefit from anchoring), compared with their peers. We administered 3 protocols: (1) The standard psychoacoustic protocol, where in each trial one of the tones, the reference tone (consistently the lower one), has a fixed frequency (RL); (2) A protocol without a repeated reference (NR); (3) A protocol where the repeated reference tone is always presented first (R1).

We conducted a repeated measures mixed factor ANOVA analysis with protocol (RL, NR, and R1) as within-subject factor and group (dyslexics and controls) as the between factor. The ANOVA showed an overall group effect, F(1, 91) = 30.62, p < 0.001, indicating that dyslexics performed worse than controls, and an overall protocol effect, F(2, 182) = 143.39, p < 0.001, indicating that performance in both repetition protocols was better than in the NR protocol. Importantly, there was a significant interaction of group and protocol, F(2, 84) = 3.49, p < 0.05, reflecting dyslexics' smaller gains from the reference containing protocols. As shown in Fig. 1, the most notable inter-group difference was found in the R1 protocol, where performance crucially gained from the combination of a repeated reference frequency and a repeated temporal position.

Our second aim was to assess whether anchoring deficits in frequency discrimination are a specific characteristic of Dyslexia, or, alternatively, a general characteristic of attention disorder. We thus conducted another repeated measures mixed factor ANOVA analysis with protocol (RL, NR and R1) as within-subject factor and group (ADHD and controls) as the between factor. This analysis showed that participants with ADHD did not differ in their performance from the control group (group and interaction effects non-significant). As can be seen in Fig. 1, controls (blue columns) and ADHD (green columns) participants had very similar thresholds in all protocols. In contrast, dyslexics (red columns) performed poorly across the board, with particular difficulties in the easiest, R1 protocol. These findings suggest that anchoring difficulties are specifically associated with reading disability, even among academically high achieving individuals.

The third aim of this experiment was to assess whether dyslexics' impaired anchoring can be accounted for by differences in musical education, since musical education may influence the sensitivity to anchors and repetitions (e.g. Parbery-Clark et al., 2011). Indeed, the prevalence of formal musical education was lower in the dyslexic group (control: 20/49, ADHD: 16/31; dyslexics: 12/44). Moreover, a repeated measures ANOVA on thresholds from the three protocols showed that participants with formal musical background (>1 year, see methods) had significantly lower thresholds, F(1, 112) = 8.64, p < 0.01, in line with previous literature. However this effect was significant in the control group only, F(1, 42) = 8.74, p < 0.01. Among dyslexics and ADHD participants, individuals with and without musical background had similar thresholds, dyslexics: F(1, 41) = 0.82, p > 0.05; ADHD: F(1, 29) = 1.54, p < 0.05, despite a tendency to lower thresholds among those with a musical background.

To examine the possibility that the difference in the impact of musical training resulted from low-statistical power due to a smaller proportion of musically trained individuals among our dyslexic participants, we re-calculated the effect with only 12 (as in the dyslexic group) musically trained controls (repeated measures ANOVAs were performed on 50 random samples of 12 trained individuals from the control group). The effect of musical education in the control subgroup remained significant, average F(1, 33) = 6.46, p < 0.02, suggesting that formal musical education may have a differential impact on controls' discrimination skills compared with those of individuals with learning disabilities.

We further calculated the performance of the subgroups of controls and dyslexics with no musical training in frequency discrimination, and found the same pattern of results. A repeated measures ANOVA with group as the between-subject factor and the 3 frequency discrimination protocols as within-subject factors, showed a main effect of group, F(1, 53) = 12.96, p < 0.001, main effect of protocol, F(2, 106) = 80.72, p < 0.001, and an interaction effect, F(2, 106) = 3.34, p < 0.05, indicating that the inter-group difference in musical education does not account for the inter-group differences in thresholds and in anchoring abilities.

Experiment 2: Verbal working memory with and without repetition in controls and dyslexics

This task contained two protocols and was designed to manipulate cross-trial repetition of syllables and to assess its impact on the performance of each group. We reasoned that the repeated use of the same syllables and same sequences would facilitate retention and retrieval due to automatic anchoring mechanisms. We further predicted that this effect would be smaller among dyslexics due to their less efficient anchoring abilities.

Overall, controls' scores were better than dyslexics. A 2-way ANOVA on syllable score with group and protocol as fixed factors revealed highly significant main effects of group, F(1, 54) = 12.51, p < 0.001, and protocol, F(1, 54) = 54.47, p < 0.001. In addition, there was a significant interaction effect, F(1, 54) = 5.1, p < 0.05, indicating that though both groups gained from repetition, controls gained more. As can be seen in Fig. 2, mean scores increased by 3 (SD = 2.4) with repetition in the control group, whereas in the dyslexic group they increased only by 1.6 (SD = 2.21). Maximal spans increased on average by 1.6 (SD = 1.4) and 1 (SD = 1.39).

Correlation between thresholds in frequency discrimination, syllable span and reading

Frequency discrimination thresholds and syllable spans were correlated with reading accuracy among controls. However, in both tasks, a significant correlation was found only with the protocols
Note that both FD-R1 and Syllable REP protocols contain ordered stimulus repetitions.

Table 2

<table>
<thead>
<tr>
<th>Condition</th>
<th>Syllable</th>
<th>Frequency Discrimination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>No Rep</td>
<td>0.44*</td>
</tr>
<tr>
<td></td>
<td>REP</td>
<td>0.15</td>
</tr>
<tr>
<td>Dyslexics</td>
<td>No Rep</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>REP</td>
<td>0.48**</td>
</tr>
</tbody>
</table>

*p < 0.05  **p < 0.01.

containing ordered repetition (Syllable Span: REP: r = 0.43, p < 0.05; NS: r = 0.22, ns; FD: R1: r = 0.4, p < 0.01; NS: r = -0.19, ns). On the other hand, neither reading scores, nor frequency discrimination thresholds or syllable spans were correlated with general reasoning abilities (i.e. scores in Block Design). None of the above correlations were found in the dyslexic group.

To examine whether common anchoring mechanisms underlie the repetition-induced gain in frequency discrimination and in verbal working memory, we calculated the correlations between performance in the various protocols of frequency discrimination and syllable span. Table 2 shows that among controls the correlation between repeated and non-repeated protocols of each task was not significant. However, performance in protocols that contained both stimulus and temporal consistencies (FD-R1 and Syllable-Rep) was highly correlated, suggesting common verbal and non-verbal anchoring mechanisms. In addition, there was a significant correlation between the performance in the protocols with no cross trial repetition (FD-NR and Syllable-NR), which require explicit working memory, suggesting that explicit working memory mechanisms may also be common to verbal and non-verbal stimuli. No such correlations were found in the dyslexic group.

Experiment 3—Repetition effects in NW reading, in controls and dyslexics

In this experiment participants were asked to read a list of 60 NWs, composed of 5 different items. We expected that item-specific repetition would lead to a significant improvement in reading rate, based on implicit anchoring to the phonological sequence composing the repeated non-words. We predicted that this anchoring effect would be reduced in the dyslexic group, resulting in a gradual increase in between-group difference, particularly for reading the most challenging, least regular NWs.

Fig. 3 shows that the overall reading rate of both groups increased along the task, both within and across the two assessment days. An omnibus ANOVA, with group as between-subject factor, and NW-encounter and day as within-subject factors showed a main effect of encounter, F(10, 410) = 147.24, p < 0.001, and a main effect of day, F(1, 41) = 45.85, p < 0.001. Fig. 3 further shows that dyslexics were generally slower than controls (main effect of group), F(1, 41) = 125.79, p < 0.001. Moreover, they were particularly slow with the two most irregular NWs, in spite of the repeated encounters. A significant difference was found when comparing reading duration between the two long regular NWs and the long irregular NW, F(1, 41) = 45.18, p < 0.001. Similarly, reading time of the short irregular NW versus the long regular NWs showed an interaction effect between word and group, F(1, 41) = 6.11, p < 0.05, indicating a larger gap between the groups for the more irregular NW, despite it being shorter.

Fig. 3a shows the dynamics of reading rate as a function of encounter number for the long, regular and irregular NWs. Among dyslexics, the cost of irregularity (measured by the irregularity index, the ratio between reading duration of irregular and regular words) remained stable across encounters, whereas in the control group it was almost eliminated by the end of day 1. Fig. 3b shows the irregularity index in the first 4 and in the 7th to 10th encounters in each of the 2 assessment days. While initial irregularity indices were similar in both groups, dyslexics’ index hardly changed whereas controls’ became nearly 1, indicating that the cost of irregularity was nearly eliminated (group × encounter interaction), F(1, 41) = 43.3, p < 0.05. At the beginning of the second day, both groups got back towards their initial level of performance, yet improved with encounters. The emergence of inter-group differences in the irregularity indices directly shows the difference in the efficiency of their anchoring.

Finally, we analyzed reading accuracy as a function of repetition, session and NW regularity. As expected, controls were more accurate, F(1, 39) = 36.21, p < 0.001, though both groups made
errors, as shown in Fig. 4. As expected, both groups made more errors in irregular than in regular NWs, \( F(1, 39) = 110.18, p < 0.001 \). However, the difference between the groups was larger for irregular than for regular NWs, group \( \times \) NWs-type interaction, \( F(1, 39) = 39.85, p < 0.001 \). In contrast to rate, accuracy did not improve, neither within nor across sessions and participants tended to repeat (i.e. anchor to) their initial errors.

3.3. Sustained attention

The CPT profile of individuals in all groups was fairly heterogeneous, in line with previous studies (August & Garfinkel, 1990; Dykman & Ackerman, 1991). We could thus ask whether scores in sustained attention (CPT scores) are correlated with performance and/or anchoring in our tasks. We found that CPT scores were not significantly correlated with performance in either of the frequency discrimination tasks, the syllable span tasks, or reading tasks in any of the groups.

Finally, we asked whether CPT scores (ADHD-likeliness) was predictive of reading abilities more than performance on the FD-R1 task, within the ADHD and the dyslexic groups combined. A stepwise regression was performed on all learning-disabled participants, with overall CPT score and R1 thresholds as predictors. R1 thresholds explained over 10% of the variance in reading scores, whereas CPT scores were not predictive.

4. Discussion

We found that adult individuals, with high academic education, above average non-verbal cognitive abilities, and a specific reading disability, are not able to effectively utilize stimulus regularities such as cross trial repetition of stimulus patterns. Similar difficulties were observed in frequency discrimination, verbal memory and phonological decoding. Moreover, among controls, only performance in protocols with stimulus repetition, of either frequency discrimination or memory span, was correlated with reading accuracy. These correlations suggest that performance in tasks aimed to measure phonological skills is influenced by anchoring abilities.

Among control participants, performance in frequency discrimination and in syllable span was correlated between protocols with temporally ordered cross trial repetition. This correlation suggests that, within the anchoring window, common mechanisms underlie the memory for speech and for simple tones. In addition, performance was correlated between protocols with no stimulus regularities, which put heavier load on working memory. This correlation suggests that also explicit, short-term working memory, mechanisms are common across different types of auditory stimuli.

This pattern of correlations across tasks using similar repetition protocols was not found within the dyslexic group. Thus, on the one hand, dyslexics showed poor anchoring across tasks. On the other hand, the degree of anchoring difficulties was not correlated across tasks, and was not a predictor of reading skills. This difference between control and dyslexic participants may stem from dyslexics’ usage of alternative strategies in tasks that are not specific to dyslexics’ reading abilities more than performance on the FD-R1 task. Within the ADHD and the dyslexic groups combined. A stepwise regression was performed on all learning-disabled participants, with overall CPT score and R1 thresholds as predictors. R1 thresholds explained over 10% of the variance in reading scores, whereas CPT scores were not predictive.

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The study described above (Willburger & Landerl, 2010) was conducted with German dyslexics. Thus a third interpretation to the difference in results is that German dyslexics may have a different cognitive and perceptual profile than Hebrew and English dyslexics. Recent literature (e.g. Wimmer et al., 2010; Ziegler et al., 2010) suggests that different writing systems pose somewhat different demands on phonological awareness, have been reported to reach high reading accuracy even with German pseudo-words, so that their main remaining difficulty is very slow reading (e.g. Frith, Wimmer, & Landerl, 1998). However, dyslexics in English and Hebrew, which have deep orthographies (Landerl, Wimmer, & Frith, 1997), are characterized by both very slow and extremely inaccurate single word and pseudo-word reading. An interesting, and perhaps related observation regarding German dyslexics was reported by Lachmann, Berti, Kujala, and Schröger (2005). They found that the subgroup of dyslexic children, who had specific difficulties in gaining from high (versus low) frequency words, also had impaired mismatch negativity to phonemic and tonal deviants. Given that poor mismatch negativity may be an indicator of poor sensitivity to sound regularities,
this observation suggests that perhaps poor anchoring specifically characterizes this subgroup of German dyslexics. Poor anchoring may impede their ability to form a robust representation of repeated sound sequences.

A complementary question that arises from the current study is whether impaired anchoring may account for dyslexics’ poor performance in additional tasks, which were not assessed here. A classical task administered to dyslexic children is the rapid automatized naming task (RAN; Denckla & Rudel, 1976a, 1976b; Wolf et al., 2000), which motivated the serial NW reading task that we designed and administered in this study. In both procedures, participants are asked to identify a series of elements, which is composed of 4–5 different items, each repeated about 10 times. The anchoring deficit hypothesis predicts that impaired anchoring will lead to slow naming in this procedure (Ahissar, 2007; Ahissar & Oganian, 2008 though see Di Filippo, Zoccolotti, and Ziegler, 2008). Interestingly, slower naming in RAN is also characteristic of individuals with ADHD who have no phonological deficits (Rucklidge & Tannock, 2002). Thus, slow naming in RAN may reflect generally poor serial identification (as is the case for individuals with ADHD) and inefficiency in utilizing stimulus repetition, perhaps in an additive manner.

While poor anchoring was found in all three tasks that we assessed, it did not account for all aspects of inter-group differences in our study. In all three types of tasks, there was an overall inter-group difference in addition to the significant inter-group difference in the benefit from stimulus regularities. The overall group effects indicate that the deficits of adult dyslexics are not limited to impaired benefits from ad-hoc statistics. These broader difficulties may reflect additional basic deficits.

However, an alternative interpretation is that the broader difficulties reflect the cumulative, long term result of poor ad-hoc anchoring. Deficits in anchoring may lead to poor learning of language-specific phonological regularities, which are important for fast and correct reading in any language. This interpretation is consistent with the concurrence of generally poor task performance (as reflected in the group effects we found) and anchoring deficits (revealed by group \times condition interactions). Moreover, it is consistent with a recently reported observation that children with phonological deficits have no general difficulties in perception (e.g. speech in noise) per se, but have difficulties in retaining accurate representations of recently presented reference stimuli (Nittrouer et al., 2011). The authors suggested that this type of deficit may lead to a long-term development of fuzzier categories, in line with our interpretation.

A third interpretation of the relations reflected in the concurrence of general task difficulties and impaired anchoring is that dyslexics’ poor anchoring results from their poor long-term representations rather than induces them. This interpretation is less likely given that studies characterizing children’s deficits (Ahissar et al., 2006; Nittrouer et al., 2011) find deficits that are more specific to anchoring compared with studies of adults, like the current study.

A fourth interpretation is that the relations between anchoring abilities and the quality of long-term representations are reciprocal rather than unidirectional. In other words, anchoring mechanisms may be an important tool for language acquisition, and once regularities are adequately represented, they may be easier to anchor to. Indeed, it has been shown that humans are sensitive to regularities in sound sequences already at the age of 8 months (Saffran, Aslin, & Newport, 1996). This sensitivity enables quick (within seconds to minutes) acquisition of word segmentation based on syllabic temporal regularities (Saffran, Johnson, Aslin, & Newport, 1999; Saffran, Newport, & Aslin, 1996). Adequate acquisition of these regularities subsequently facilitates fluent reading of phonologically regular words (Bonte, Poelmans, & Blomert, 2007) and an impairment of this ability concurs with language disability (Evans, Saffran, & Robe-Torres, 2009). Moreover, although the formation and automatization of the link between orthographic and speech sound representations (e.g. phonemes, syllables, Ziegler & Goswami, 2005) is an important aspect of reading acquisition, particularly at its initial stages, the level, at which this mapping is implemented, is crucially affected by knowledge of words and phonotactic regularities. With practice, serial grapheme to phoneme mapping is replaced by recognition of sets of graphemes at the sub-semantic level (“chunking”), which can be mapped to syllables, and perhaps even to larger phoneme sets which can then be mapped to semantic categories (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Snowling, Gallagher, & Frith, 2009). Although the semantic level is irrelevant when reading pseudo-words, orthographic to phonological decoding still benefits from similarity to familiar phonological and morphological structures.

Given the complexity of determining the direction of causality between poor anchoring and poor long-term representations, particularly given that it is likely to be reciprocal, our NW reading task is of unique importance. This task tracks the dynamics of reading as a function of encounter number with phonologically novel stimuli. It thus probes the process of regularity detection de novo, in reading. Its results showed that dyslexics are slower in the process of “regularization” of irregular words. In this task this process can only be based on ad-hoc regularity detection and retention.

Taken together, the main impact of our findings for future research of dyslexia is that they imply that its focus should shift from studying language-specific processes (Snowling, 1998) to general mechanisms for detecting simple statistical regularities in the pattern of auditory stimulations. This conceptualization is consistent with hypotheses of poor selective attention as well as hypotheses of increased noise sensitivity (Hari & Renvall, 2001; Sperling et al., 2005, 2006). Both may result from impaired implicit learning, which hampers efficient formation of stimulus specific predictions. It may also be consistent with hypotheses of poor temporal processing, if dyslexics’ difficulties in this domain result from poor formation of specific temporal predictions based on recent temporal regularities (e.g. Ahissar et al., 2001).

Based on our findings, we propose the following general dynamic framework: when an event begins (i.e. we enter a room, begin a conversation), its “gist” is quickly identified based on a crude bottom-up analysis supplemented by top-down predictions regarding the expected event (Ahissar, Nahum, Nelken, & Hochstein, 2009; Hochstein & Ahissar, 2002). This crude identification triggers a context-specific set of expectations, which propagate backwards, along the reverse direction of the processing hierarchy from higher to lower levels of processing, where acoustic details are represented. With repeated stimulus presentations, automatic anchoring mechanisms refine the details of these predictions. We posit that dyslexics are less efficient in adjusting their implicit set of local predictions to the context-specific stimulus statistics. The exact characterization of the local predictions impaired in dyslexia requires further studies.

The anchoring hypothesis has additional conceptual implications that were not directly assessed in this study. First, the characteristics of the anchoring window in terms of timing and capacity are still not understood. This window lasts longer than the 2–3 s characterizing explicit working memory, and has a larger capacity. Although both its capacity and its duration are larger than that of explicit working memory, allowing it to track regularities across seconds, they are still limited and hence impose important constraints on the nature and complexity of regularities that it can track. Understanding these constraints will...
thus be informative in tapping the limits of human statistical learning abilities.

Second, the relationship between musical skills and language acquisition, in the general population and among individuals with reading disability though studied, should now be further explored from the perspective of regularity detection. The hypothesis that common mechanisms track regularities in simple sound sequences and in speech suggests that linguistic abilities may be boosted by musical education. This suggestion is in line with current literature. For example, musical aptitude at the age of 4–5 is predictive of reading performance (Anvari, Trainer, Woodside, & Levy, 2002). Moreover, training with tone discriminations improves verbal working memory among individuals with reading and language disability (Banai & Ahissar, 2009). The specific link to regularity detection, as suggested by the anchoring hypothesis, has only recently been addressed (Strait et al., 2011). Our findings together with these recent results imply that the causal relations, including their “therapeutic” implications, should be further explored. In the current study we found that although our dyslexic participants had less musical education than our control participants, this difference does not account for their poorer anchoring. In fact, unlike controls, among dyslexics, individuals with and without formal musical education did not differ in their frequency discrimination abilities. Whether this null effect in the dyslexic group stems from less musical practice despite seemingly equal formal training, or from reduced training effects, is beyond the scope of the current study and remains a question for future research.

In summary, the current study shows that dyslexics’ anchoring deficit is reflected in their performance at different levels of auditory processing—from simple 2-tone frequency discrimination to fluency of single word reading. We propose that dyslexics’ impaired anchoring abilities reduce their perceptual acuity, limit their verbal memory span and impair their acquisition of phonotactic regularities, which impedes their acquisition of adequate reading skills.

Acknowledgments

We thank the Israeli Science Foundation and the National Institute for Psychology in Israel for supporting this work. We thank Tali Biron, Yael Bogen, Tali Krakover, and Adi Meir for their help in administering this study.

Appendix A. Supplementary Information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2012.04.014.

References


