

Deficient anchoring – a potential link between perceptual and cognitive difficulties among learning impaired individuals

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Dyslexia – a substantial difficulty in acquiring fluent and efficient reading – is the most common form of learning disability, present in more than 80% of the individuals diagnosed with learning problems (Snow, Burns, & Griffin, 1998). While early academic research described dyslexia as a visual disorder, "congenital word blindness" (e.g., Morgan, 1896; Orton, 1928), studies in the last 40 years revealed that a major obstacle in learning to read involves the auditory system and particularly the phonological system. Phonological processing relates to processing of speech sounds, including the smallest components, phonemes. Individuals with dyslexia have difficulties mapping (or consistently matching) between letters (the basic visual elements in reading) and the phonemes they represent (see Shaywitz, Morris, & Shaywitz, 2008; Vellutino, Fletcher, Snowling, & Scanlon, 2004 for recent reviews). Dyslexic individuals also have difficulties in verbal working memory (e.g. their verbal span in terms of the number of digits they can accurately repeat is smaller than expected from their age, education and non-verbal intelligence) and in rapid naming of letters, digits and other symbols. The attempt to describe these characteristics as reflecting a single core deficit led to the "phonological deficit hypothesis", which suggests that dyslexics' core deficit resides in their poor representations of speech constituents, i.e. phonological representations (Snowling, 2000).

A complementary aspect of the phonological hypothesis is the concept that dyslexics' difficulties are specific to phonological representations and do not encompass other auditory, visual or language impairments. Yet, a growing body of evidence indicates that individuals who read poorly often exhibit broader difficulties, in linguistic (Snowling, 2008), perceptual (Ahissar, Protopapas, Reid, & Merzenich, 2000; Amitay, Ahissar, & Nelken, 2002), motor coordination (Nicolson, Fawcett, & Dean, 2001), and attention demanding tasks (Hari, Renvall, & Tanskanen, 2001). These observations led researchers to propose more general accounts of dyslexia involving

sensory and sensory-motor systems in addition to the language system (e.g., the magnocellular hypothesis, Stein & Walsh, 1997). Other studies gradually viewed dyslexia as a result of a combination of risk factors (Bishop, 2006; Pennington & Bishop, 2008; Snowling, 2008), rather than a single core deficit.

The findings that dyslexic individuals have non-phonological deficits are not novel. In the early seventies Tallal and Piercy (1973) suggested that individuals with language disability have general difficulties in processing rapidly presented brief stimuli. Tallal later suggested (1980) that this basic impairment also characterizes the majority of individuals with reading difficulty. Tallal reasoned that since speech is composed of fast sequences of brief stimuli, such a deficit would impair speech perception and consequently the accuracy of phonological representations, phonological memory and reading. In a later collaboration with M. Merzenich, they managed to train a group of children with language disability, on a combined training protocol based on this hypothesis (Merzenich et al., 1996; Tallal et al., 1996) with impressive success.

Given later findings that the difficulties of individuals with dyslexia are not specific to briefly presented stimuli, we asked whether one could account for a large portion of dyslexics' difficulties with an alternative single account. Our quest for such a putative "core" deficit is described in this chapter.

Auditory discrimination deficits in dyslexia and the impact of the assessment procedure

Our first candidate, given the mild yet wide range of difficulties, was a more general perceptual impairment not limited to fast processing. To assess this hypothesis we tested a broad, i.e. large and heterogeneous with respect to academic achievements, population of adult dyslexics with a wide range of simple auditory tasks.

The original paradigm used by Tallal for assessing dyslexic individuals' auditory processing was a simple 2-tone identification task. In this task listeners were asked to identify the relative frequency of 2 brief tones that greatly differed in their frequency (e.g. 800 and 1200 Hz), and that were presented with varying inter-tone time intervals. Tallal found that dyslexics' performance was impaired when the time interval separating the two tones was very brief (<0.25 s), whereas their performance with

Deficient anchoring

longer time intervals was similar to that of controls. These observations led her to propose the 'fast temporal processing' hypothesis.

However, we found that a large proportion of the dyslexic population had difficulties both when asked to make fine discriminations with decreasing time intervals and with decreasing frequency differences (Ahissar et al., 2000). Thus, simple frequency discrimination was also difficult when the limiting factor was frequency difference. Moreover, the degree of difficulty was highly correlated with the degree of reading difficulty. Similar findings were reported by McArthur and Bishop (2004) for children with language impairment.

In a subsequent study we asked whether this impairment could be mapped to a specific low-level mechanism in the auditory system but found no such specificity (Amitay et al., 2002). At the same time we asked whether perceptual impairments could be related to a specific higher level mechanism, and found that the poorer performers had particularly poor verbal working memory skills (Banai & Ahissar, 2004), and poorer performance in cognitive tasks that are taxing for working memory.

The finding that poor perceptual performance is clustered with poor verbal working memory could be the outcome of poor executive functions, poor retention, or poor perception. For example, a comparison of two stimuli, which one is often asked to do in a simple perceptual task, requires the perception of the first stimulus and its retention, the perception of the second stimulus, and finally, a comparison between the two. We therefore asked which of these aspects impedes dyslexics' performance. In order to distinguish between the impact of working memory and that of stimulus processing, we designed two similar same-different tasks, and administered them with two sets of stimuli. The tasks differed in working memory load. One task was a simple same/different task, which included 2 stimuli in each trial, and hence had a low load. The other task was a same/different task that included 3 stimuli in each trial and listeners were asked whether the 2nd or the 3rd stimulus was identical to the 1st. This task had a higher memory load. We administered these 2 tasks with simple tones and with complex speech signals (see Figure 1, Banai & Ahissar, 2006). We reasoned that if processing of auditory stimuli is impaired, participants will perform poorly when complex stimuli are used. However, if working memory is the bottleneck, participants

will perform poorly when working memory is taxed. We found that with both types of stimuli, dyslexics performed the easy task as well as controls. On the other hand, regardless of the stimulus, dyslexics were significantly poorer on the more difficult task. These findings suggest that poor working memory skills impaired dyslexics' performance in simple auditory tasks.

But what was it in the more demanding task that posed the main bottleneck for dyslexic individuals? In the demanding 3-tone same-different task, the impaired component could be the retention of stimulus representation through intervening stimuli, or the comparison operation itself. In order to distinguish between these two alternatives, we designed a new version of the 2-tone discrimination task, the *no-reference* version (see Figure 2, Ahissar, Lubin, Putter-Katz, & Banai, 2006). In our original tasks as well as in most psychophysical assessments, at least one of the tones in each trial is a repeated reference tone (in our case a 1000 Hz tone), and the other tone(s) varies from trial to trial based on subjects' performance. In the general population, these protocols yield better performance compared to protocols in which there is no repetition of the reference across trials. The benefit in perceptual resolution due to the use of a repeated reference was first observed sixty years ago by Haris (1948), who attributed it to "psychological anchoring". Though no mechanism was specified, the idea was that listeners use the internal representation of the reference based on a series of trials instead of the recently presented stimulus. In the new, *no-reference* paradigm there was no fixed reference tone that repeated across trials. Therefore, anchoring was not possible and on-line comparison of the two stimuli was required on each and every trial. We reasoned that if dyslexics' impairment lies in the comparison process, then they will have more difficulties with the no-reference paradigm, whereas if their deficit lies in the retention of the reference through intervening stimuli, they will have more difficulties with the standard (reference) containing protocol.

The results were clear, as shown in Figure 2. Performance of dyslexic participants did not differ from controls' in the difficult, comparison requiring, *no-reference* paradigm. However, in contrast to controls, dyslexics' performance did not improve when the same reference was repeated across trials (Ahissar et al., 2006), indicating that dyslexics' ability to construct and utilize the reference as an internal anchor is

Deficient anchoring

impaired. In terms of our initial questions, dyslexic individuals have difficulties in retaining accurate representations of recently presented stimuli across intervening stimuli. Consequently, they have to apply a 2-tone comparison operation on every trial, even under conditions in which the general population beneficially replaces on-line comparisons with stimulus retrieval.

Dyslexics' performance under the reference paradigm, but not under the no-reference paradigm, was highly correlated with their phonological memory scores, suggesting that their difficulties in these two types of tasks are limited by a common bottleneck. The interpretation of a common bottleneck was further supported by a subsequent training study that we conducted with dyslexic teenagers (unpublished data), in which systematic training on 2-tone discrimination tasks (using consistent reference stimuli) improved both auditory anchoring ability and phonological memory (but not performance of unrelated cognitive tasks).

Anchoring and the biology of dyslexia

During the past 15 years, many imaging studies tried to pinpoint brain sites with abnormal activity. The phonological deficit hypothesis predicts that the areas and processes which would be affected in dyslexia are areas specifically related to reading and to processing of phonological information. Indeed, dyslexics' posterior areas involved in phonological processing, and areas involved in visual word identification show reduced activation in imaging studies (reviewed by Shaywitz & Shaywitz, 2008). Moreover, connectivity between and within areas involved in phonological and orthographic aspects of reading may also be affected (Cao, Bitan, & Booth, 2008; Klingberg et al., 2000; Paulesu et al., 1996; Silani et al., 2005; Steinbrink et al., 2008). However, abnormal activity was also found in areas which are in no way specifically related to reading, including visual areas (e.g., area MT, Demb, Boynton, & Heeger, 1998; Eden et al., 1996), auditory areas (Heim et al., 2000; Helenius, Salmelin, Richardson, Leinonen, & Lyytinen, 2002; Kraus et al., 1996; Nagarajan et al., 1999; Stoodley, Hill, Stein, & Bishop, 2006) and the cerebellum (Eckert et al., 2003; Leonard et al., 2001), when measured with stimuli and tasks that activate these areas.

Studies assessing the dynamics of activity (measuring evoked responses) also found abnormal patterns distributed along the auditory pathways. For example, Banai, Zecker, Nicol & Kraus (2005) have shown that at-least a sub-group of poor readers had abnormal automatic brain responses (ERPs) to the speech syllable /da/, when these were measured from either the brainstem or the cortex. We should note that in that and in most other ERP studies, a small set of stimuli is typically used repeatedly. Thus, impaired responses do not dissociate between the affect of initial and that of subsequent stimulus presentations. A more direct evaluation of the impact of recent stimulus presentations was obtained in a study by Bonte & Blomert (2004), who assessed dyslexics' implicit phonological priming, as reflected by their ERP response. They asked children to perform a lexical decision task on an orally presented word, and primed it by presenting a phonologically similar word (or a phonologically unrelated word as control) one second earlier. Dyslexics' early priming-related responses (N1-N2, 100-200ms) were abnormal, whereas their late priming-related response components (N400) were adequate. Bonte & Blomert interpreted this finding as indicating a deficit at the earlier, perceptual stage, rather than at the later phonological-lexical stage. Taken together, these findings suggest early, perceptually related sites of impaired processing, which are not specific to phonological processing.

The neural mechanisms underlying anchoring are still not understood. Perhaps the closest phenomenon measured at the system's level is the mismatch negativity response (MMN). MMN is the evoked response (ERP) produced by the auditory cortex, with a frontal contribution, when an oddball stimulus is presented in a sequence of identical stimuli (Näätänen, 1992). The MMN response is recorded even when participants are busy in other activities. Detecting the oddball requires formation of a stimulus-specific memory trace (anchor) for the repeated standard. According to the impaired anchoring hypothesis, dyslexics are expected to have poor MMN responses, particularly under conditions which tax the retention of the standard. Yet anchoring under the typical MMN protocol is typically not too challenging since the standard stimulus is presented sequentially with occasional oddball stimuli, and thus retention through intervening stimuli is not necessary.

Deficient anchoring

Many studies assessed MMN responses to frequency, duration and phonetic deviants among dyslexics and among individuals with language disability. Results are mixed perhaps due to sampling small populations with a small signal (reviewed by Bishop, 2007) and perhaps due to different degrees of anchoring demands. Interestingly, the proportion of studies that found reduced sensitivity to frequency deviances is larger than those that found reduced sensitivity to phonetic contrasts. We predict an increased deficit under conditions that tax the formation of the repeated reference. A partial support of this hypothesis was provided by a recent MMN study which found impaired MMN only under more demanding anchoring conditions (Kujala, Lovio, Lepisto, Laasonen, & Naatanen, 2006).

The mechanisms underlying the mismatch negativity are still heavily debated (see Jaaskelainen et al., 2004; vs. Naatanen, Jacobsen, & Winkler, 2005). Yet, they are at least partially related to adaptation mechanisms that can also be measured at the level of single neurons. The typical measure of adaptation is the reduction in the response as a function of neuronal activation, which can be induced by repeated stimulus presentations. Recent studies suggest that neural adaptation can be highly specific to the frequency of the repeated stimulus. That is, the pattern of reduced activity shows greater frequency selectivity than that revealed in standard measures of response selectivity (Ulanovsky, Las, & Nelken, 2003). These findings suggest that adaptation processes indeed increase perceptual resolution, and their impairment, as suggested in the case of dyslexia, may reduce perceptual resolution.

Anchoring and cognitive/behavioral characteristics of dyslexia

1) Poor resilience to noise

A characteristic symptom of learning disability, which is shared by but not specific to dyslexia, is difficulties in perceiving speech in 'noisy' or distracting listening environments (e.g., Boets, Ghesquiere, van Wieringen, & Wouters, 2007; Ramirez & Mann, 2005). This observation was previously related to a general lack of ability to "handle" external noise, without specifying an underlying mechanism (Amitay et al., 2002; Hartley & Moore, 2002). The hypothesis that individuals with dyslexia have generally poor anchoring mechanisms naturally accounts for this observation. Since the stream of stimuli is not composed of independent elements, anchoring to recently

presented stimuli provides the perceptual system with better predictions of incoming stimuli. We propose that developing better expectations (or templates) is the main mechanism for improving resilience to noise. Rather than dumping the irrelevant noise we learn to better retrieve the expected stimulus, at the cost of being perceptually biased towards recently presented stimuli ("anchors"). When these anchoring mechanisms fail, perception is expected to be more sensitive to noise.

To directly assess the relations between anchoring abilities and dyslexics' sensitivity to noise we administered two tests of speech perception in noise. In both tests we asked participants to repeat pseudo-words presented in noise (Ahissar et al., 2006). However in one condition we used a large set of words, which were not repeated during the assessment, and hence word specific anchoring was not beneficial. Under this condition we found no difference between controls' and dyslexics' performance. In the other condition, we used only a subset of the pseudo-words and each word was repeated several times within the assessment. In this condition dyslexics' performance was significantly worse than controls', suggesting that they could not effectively utilize word specific repetitions. Analyzing the pattern of errors that participants made showed that both groups tended to confuse the presented words with phonologically similar words (e.g., confusing /barul/ with /darul/, /tarul/ or /parul/). However, controls' errors were mostly limited to similar pseudo words that were actually used during the assessment (only /parul/ in this case), suggesting that they implicitly expected that previously presented words will be repeated. Dyslexics' responses were equally likely to be words that were not part of the repeated set (/tarul/ and /darul/), suggesting that they performed each trial as if "from scratch", based only on phonological similarity, ignoring the consistencies within recent stimulus presentations. When asked at the end of the assessment, neither of the groups was able to explicitly reproduce the full set (five pairs) of pseudo-words that were used.

These results indicate that in the general population, speech perception, just like perception of simple sounds, quickly sharpens around the stimuli that were recently presented and are implicitly expected to be presented again. These dynamic processes probably play an important role in improving speech perception in noisy environments within seconds to minutes from entering these environments. For example, when we enter a noisy cafeteria, we are initially overwhelmed and our

Deficient anchoring

perception is blurred. Yet, quite rapidly, our perception clarifies around the stimuli that characterize the relevant sound source (speaker). We propose that for dyslexics, this clarification does not occur as well since they cannot automatically focus on the repeated stimuli, e.g. the characteristics of the voice, pronunciation and intonation of their attended speaker. Therefore they need to discriminate the speaker's voice and content from the background noise every time de-novo. Automatic anchoring probably occurs at multiple levels concurrently, at simple perceptual stages and at higher, more abstract, levels. At present we do not know which levels of anchoring are impaired among dyslexics and whether these are indeed the same levels across different individuals. One option is that individuals with different learning disabilities have difficulties with different anchoring levels and domains. This idea should be the subject of future research

2) **Anchoring and phonological processing deficits**

Impaired anchoring to repeated stimuli can also account for the pattern of deficits found in dyslexics' performance of phonological tasks. The phonological hypothesis proposes that phonological representations are impaired, perhaps being fuzzier and not well defined. Since there is no direct probe for measuring the adequacy of abstract phonological representations, several studies focused on the adequacy and sharpness at the input level, i.e. categorical perception of speech. Categorical perception refers to our greater sensitivity to differences between speech stimuli when they belong to different categories compared to within-categories (e.g. /ba/ versus /da/ as opposed to two different instances of /ba/ or /da/). This difference is related to our immediate identification of speech stimuli as belonging to a specific category rather than retaining their general acoustic characteristics.

Results of categorical perception studies are mixed, with a clear tendency towards finding deficits in dyslexics' categorical perception when synthetic rather than natural speech stimuli (Blomert & Mitterer, 2004) were used. For example, using synthetically produced syllables, Godfrey Syrdal-Lasky, Millay, & Knox (1981) reported that controls showed clear categorical perception whereas dyslexics' performance was fuzzier and less consistent. Controls showed the expected sharp transition between perceiving one syllable and perceiving the other, whereas dyslexic participants showed a shallower slope (see illustration in Figure 3, top). We propose

that with synthetic or impoverished stimuli, which are not clearly perceived as either one or the other syllable on first encounter, listeners' slopes may reflect their reduced ability to consistently respond to the same stimuli with the same tag. In the general population this consistency is supported by anchoring to the tagging of a specific recent presentation. This mechanism is impaired in dyslexia. The impaired anchoring hypothesis thus predicts that controls and dyslexics would not differ in their categorization of synthetic speech during first encounters, which will be variable and inconsistent across individuals. Inter-group differences would evolve with repeated presentations. Controls' responses (even if incorrect) would be more consistent across presentations than those of dyslexics, who would retain much of the initial variability.

Once stimuli are associated with categorical labels, this categorization is expected to affect both their identification and their discrimination performance. Therefore, controls' discrimination between synthetic stimuli that belong to the same category will decrease with their increasingly more consistent categorization, whereas their discrimination between categories will concomitantly improve. This effect will be much weaker in dyslexics. Thus, their discrimination performance will not have the characteristic shape of categorical perception [see illustration in Figure 3, bottom]. Indeed, recent studies demonstrate that with synthetic stimuli, dyslexics' categorical perception is less accurate than that of controls whereas their within category discrimination is better (Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008; Serniclaes, Van Heghe, Mousty, Carre, & Sprenger-Charolles, 2004). According to the anchoring deficit hypothesis, this inter-group difference is expected to appear only when discrimination is assessed after identification learning had already occurred (as in the Godfrey et al., study) and not if assessed first.

A similar effect is expected when the task requires categorization of novel non-phonological stimuli, which can also be aided by recently formed anchors. Such findings were recently reported (Goswami et al., 2002).

A recent study by Ramus & Szenkovits (2008), which was designed to assess the adequacy of dyslexics' phonological representations by administering a broad battery of phonological tasks, reached a similar conclusion. Namely, manipulating phonological difficulty did not affect dyslexics' performance more than it affected that

Deficient anchoring

of controls'. However, increasing working memory load was more detrimental to dyslexics. Based on a set of studies they proposed the “difficult accessibility” hypothesis suggesting that dyslexics' difficulties reside not in the adequacy of phonological representations but in the ease and rate of accessing them. Both their findings and interpretation are in line with the anchoring deficit hypothesis, which predicts poorer access to long term representations, specifically to those which were or are similar to recently activated representations. The anchoring hypothesis further predicts poor working memory skills since these involve the retention of accurate anchors through intervening stimuli.

3) Anchoring and attention

Several groups suggested that dyslexics' main deficit involves poor attentional skills. For example, Hari & Ranvall suggested that dyslexics' attentional mechanisms, particularly those underlying switching from processing one object to processing another, are "sluggish", i.e. inefficient ("sluggish attention", summarized by Hari & Renvall, 2001). For example, their group found that dyslexics have a longer "attentional blink". This phenomenon relates to the difficulty of observers to identify 2 targets presented in rapid sequence. While individuals adequately identify one pre-defined target in a series of rapid stimulus presentations, they fail to identify the second target presented in a time window of 100-500 ms after the first. Dyslexics' "attentional blink" is longer even though they adequately identify one target. Similarly, fast search for a visual odd-ball that differs in one salient feature from other elements in an array is not impaired among dyslexics. However, laborious, element-by-element, attention-demanding search for a non-salient target is slower (Vidyasagar, 2005). The attention deficit hypothesis gains indirect support from the high prevalence of co morbidity of attention and reading disorders (e.g., Willcutt et al., 2001). Still, many individuals with an attention disorder have no reading difficulties.

The impaired anchoring hypothesis could be viewed as a specific type of impaired attention hypothesis. It proposes that with stimulus-specific repetitions, controls' performance with the repeated targets becomes both more noise-tolerant and more efficient due to improved stimulus-specific predictions. Therefore, though dyslexics' top-down attentional mechanisms are unimpaired, their bottom-up driven attentional

mechanisms are less effective since they can not utilize the gradual (automatic) build-up of predictions around repeated stimuli, which typically reduce attentional load.

In the case of "attentional blink", which is usually assessed with repeated target stimuli, performance is expected to become more efficient with repetitions. However, if dyslexics fail to anchor to the targets, more ad-hoc information should be processed and consequently target identification requires a longer processing duration. The anchoring deficit predicts that if different target stimuli were used in different trials, controls' performance would not differ from dyslexics'.

The difficulty in anchoring to repeated stimuli will also yield slower usage of cuing stimuli, which provide specific information about the target stimulus. These cues are themselves repeated stimuli, and cuing efficiency indeed typically improves with repetitions. Several studies showed that while dyslexics are able to utilize cues (Facoetti, Lorusso, Cattaneo, Galli, & Molteni, 2005), their utilization is less effective. Thus, long duration cues improve their performance whereas very brief cues, which can still be utilized by the general population, do not improve dyslexics' performance (Roach & Hogben, 2007).

Note that the anchoring deficit hypothesis suggests that rather than being slower in the rate of information retrieval from the external environment (e.g. stimulus processing), dyslexics are slower since they need to retrieve more information due to poorer anchoring abilities.

4) Sensory motor deficits

Recent findings suggest that dyslexics' sensory-motor difficulties can also be explained by an anchoring deficit. Dyslexic individuals have difficulties in implicit learning of repeated sensory-motor sequences which require a series of fast responses to visually cued positions. Whereas controls implicitly learn these sequences and perform repeated sequences better than random ones, dyslexics fail to benefit from sequence-specific repetitions (Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006). This type of impairment, i.e. a difficulty in sequence-specific learning, may be related to the hypothesis that dyslexics also tend to have a general difficulty in acquiring fluent and automatic behavior (i.e. the double deficit hypothesis) (Nicolson & Fawcett, 2007; Wolf & Bowers, 1999). However, the anchoring deficit hypothesis

Deficient anchoring

does not attribute the source of difficulty to impaired long-term modifications, but to poor ad-hoc utilization of recently presented stimuli. When the same procedure and stimuli are performed across days, the main difficulty will be apparent in within rather than across session improvement.

Anchoring and development

The anchoring hypothesis was derived from our teenager and adult studies. Given that we are studying a developmental impairment, longitudinal studies from pre-school stages should be administered in order to assess whether anchoring abilities can be reliably measured at early childhood, and whether, as the theory predicts, pre school children with anchoring difficulties develop reading difficulties later on.

An open question refers to the relations between anchoring abilities and long-term representations; specifically, whether adequate long-term phonological representations can develop even when anchoring is impaired. Our discussion above assumed two separate processes, anchoring with fast rise and decay time constants, and long-term learning. This assumption is consistent with anecdotal reports on exceedingly fast progress following short training programs of individuals with language and reading disability (e.g. Tallal et al., 1996), bridging years' gap with weeks' training. Thus, if the difficulty stemmed from anchoring while long term representations were adequate, learning may have uncovered stored abilities. Yet, the relations between short and long term improvement, should still be studied systematically.

Anchoring and the heterogeneity of dyslexia

Apart from the need to acquire developmental data, the second major aspect that needs to be assessed is the role of anchoring in proficient reading. The anchoring-deficit hypothesis proposes that various accumulative aspects of perceptual priming, which are less efficient among dyslexics, importantly impact reading fluency. The impaired processes are not the semantic aspects, which seem adequate in dyslexia, but those that relate to the format in which the information was conveyed.

Partial support for this idea was provided by a study which found impaired cross-sentence build up of syntactic priming effects in reading disabled children (Deutsch & Bentin, 1996). Morpho-syntactically incongruent words inhibited controls' responses but not those of reading disabled. However, controls' inhibition was apparent only when the congruent and incongruent trials were presented in separate blocks. On the other hand, cross-trial consistency had no effect on dyslexics' responses, in line with the impaired anchoring hypothesis.

An alternative account for the relations between impaired anchoring and reading ability is via the intermediate factor of working memory, which closely concurs with poor auditory anchoring. In that case, we would not expect one-to-one relations between poor anchoring and dyslexia, but we shall expect a high correlation. This interpretation is in line with the concept that dyslexia is the outcome of a cluster of difficulties (risk factors) rather than a single core deficit (Bishop, 2006; Pennington & Bishop, 2008; Plomin & Kovas, 2005). Thus, recent studies showed that most at-risk individuals manifest phonological processing deficits upon school entry, but only individuals in which the phonological processing deficits are part of a wider language delay, which includes receptive and expressive language skills and vocabulary (Snowling, 2008) end up developing the literacy deficit (note that the other group also had subtle difficulties though when followed to adolescence, Snowling, Muter, & Carroll, 2007).

As described above, the three main characteristics that mark dyslexics' profile are poor phonological awareness, poor phonological memory and poor rapid naming of symbols. Rather than stemming from a single core phonological deficit, as suggested by the phonological hypothesis, they could be the outcome of several different underlying factors. Thus, none of these characteristics can serve as a singular factor underlying dyslexia and typical factor analysis finds them pouncing on different factors. Impaired anchoring may denote the mechanism underlying poor working memory in general and poor phonological memory, which impedes adequate development of reading and language. Poor anchoring ability for sounds may be the factor which is genetically transmitted, as suggested by recent studies (Bishop, 2006). Our preliminary findings in the general population are in line with this hypothesis. Control individuals with poor auditory anchoring abilities, as measured by the two

Deficient anchoring

tone discrimination task, have poorer verbal memory scores than controls with better performance. On the other hand, their phonological awareness is not directly correlated with this ability. Thus, anchoring to pure tones and verbal memory scores are generally correlated. Yet if they are impaired but this is not accompanied by other language related impairments, they may not develop reading and/or language disability.

In order to assess these questions in the broad population, and to allow individuals to assess their auditory anchoring abilities, we designed an open site, <http://papi.huji.ac.il>, where individuals and research groups are welcome to enter a virtual lab and participate in a full experiment via the internet. Following assessment the site provides personal feedback to external users.

Conclusions

We described the anchoring-failure hypothesis and its strength in accounting for a broad range of dyslexics' perceptual and memory difficulties. This hypothesis suggests that dyslexics' deficit resides in the dynamics that link perception with memory, through the automatic formation of implicit stimulus-specific predictions. These anchors are formed on a time scale of seconds to minutes, and probably occur at multiple processing stages. Deciphering the developmental role of the anchoring dynamics and its specific contribution to reading proficiency remains subject for future research.

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Figure Captions

Figure 1: A 2x2 array of for assessing the role of task versus stimulus complexity

In order to assess whether dyslexics' main difficulties stem from challenges in stimulus processing or in task-related demands, we designed a simple and a more demanding task and applied both of them using two sets of stimuli, simple tone and complex pseudo-word discrimination. In the simple task, participants were presented with stimulus pairs, tones or pseudo-words (measured separately), and were asked whether they were the same or different. The more demanding task was also a same/different task, but listeners were presented with 3 stimuli ("which tone is the same as the 1st – 2nd or 3rd?" or "was the 3rd pseudo-word a repetition of the 1st or 2nd"). Though both tasks are same/different tasks and use the same basic components, the 3-stimuli task is a more demanding working memory task. From a stimulus processing perspective, the pseudo-word analysis requires a much more complicated analysis.

The figure shows average results of both groups under the four conditions. Increasing the demands of stimulus retention and comparison (right versus left column) significantly impairs dyslexics' performance, though it does not affect controls' performance. A group effect is found only under the demanding task, whereas increasing stimulus complexity does not yield a group difference.

(Top: y-axis Just Noticeable Difference (JND) in percent of 1000 Hz (i.e. 1% = 10 Hz). Bottom: y-axis % errors. Controls are denoted in blue, dyslexics in red; error bars ± 1 s.e.m.). Adapted from Ahissar, 2007.

Figure 2 - The failure to anchor to the reference stimulus

In order to assess whether it was the comparison between subsequent stimuli or the retention of stimuli that posed greater difficulties for dyslexics, we designed two very similar paradigms. In both paradigms, each trial was composed of 2 brief tones. Listeners were asked which tone is higher. At the level of single trials the tasks were the same. However, as illustrated in the top part of the figure, the two paradigms differed in the consistency of stimuli across trials. In the standard paradigm (right) a reference stimulus (denoted in green in the figure, 1000Hz in our case) is presented in every trial, either first or second. The non-reference stimulus was always higher. Thus, after several trials, listeners could skip actual comparison and identify the reference stimulus, which was always lower. At that point a comparison is replaced

Deficient anchoring

with reference retrieval. The other paradigm (left) contained no reference. At each trial both tones were randomly chosen (from a range of 600-1400Hz). Thus, listeners had to keep comparing, since there was no consistent tone repetition. The bottom plots show that both groups perform similarly when a comparison is required (left). However, only controls perform significantly better (lower thresholds) under the standard reference conditions. These results show that dyslexics' difficulties are in anchoring to repeated stimuli and utilizing consistencies to sharpen perception.

Adapted from Ahissar 2007.

Figure 3: Categorical perception experiments using synthetic syllables

In categorical perception studies, researchers create a series of stimuli that differ along a single physical dimension. Stimuli at one end of this series are perceived as one syllable whereas stimuli at the other end are perceived as a different syllable (e.g. /da/ versus /ga/). Categorical perception is manifested as a sharp transition in perception when stimuli are presented along this axis, from one syllable to the other (illustrated as the sharp transition - blue line, in the top plot). In addition, same-different discrimination between pairs of stimuli is easy across the categorical boundary and difficult within categories (blue line, bottom plot).

We propose that when synthetic syllables are used, and the continuum is not clearly perceived as either syllable 1 or syllable 2, the first response will impact subsequent decisions, and the steepness of the slope will be significantly affected by listeners' consistency across trials. Thus, the y axis represents individuals' consistency in identifying the same stimulus as the same syllable. If they are completely consistent they will always identify a given sound as either "syllable 1" (100% on the graph) or as "syllable 2" (0% on the graph), forming the expected categorical step function. Since dyslexics are less consistent in utilizing recent stimulus presentations, they will be less consistent in mapping the initially poorly defined (intermediate) stimuli. This effect will be manifested as a shallower slope (red line, top plot). The same mechanism will affect discrimination performance when assessed after identification training. Controls' performance will be affected by the prior identification practice, which improves their cross-category distinction and degrades their within category discrimination. Dyslexics will be less affected by this protocol and will show a shallower dependence on category (red line, bottom plot). Based on Godfrey et al., 1981. Adapted from Ahissar, 2007.

Figure 1.

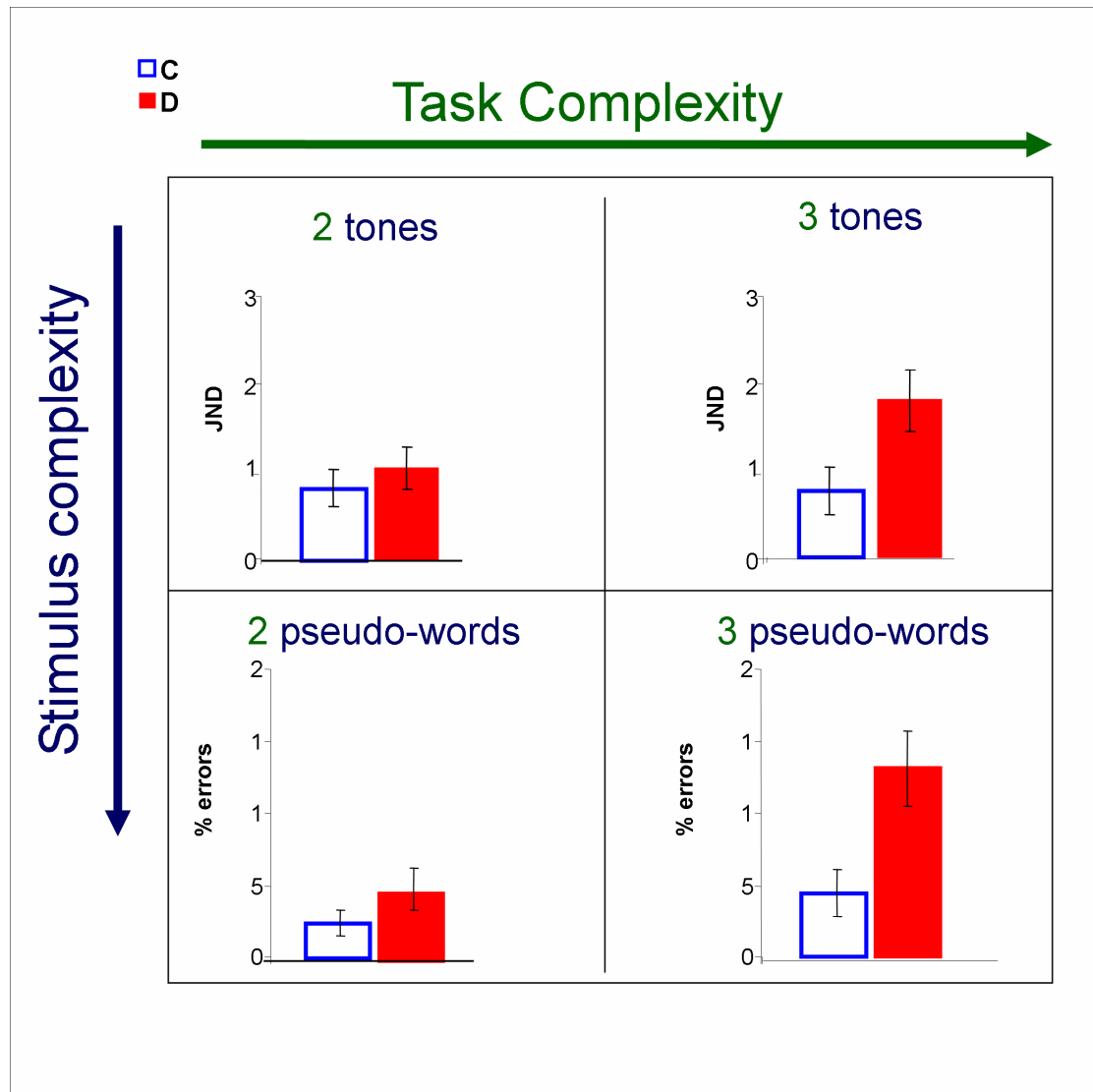


Figure 2.

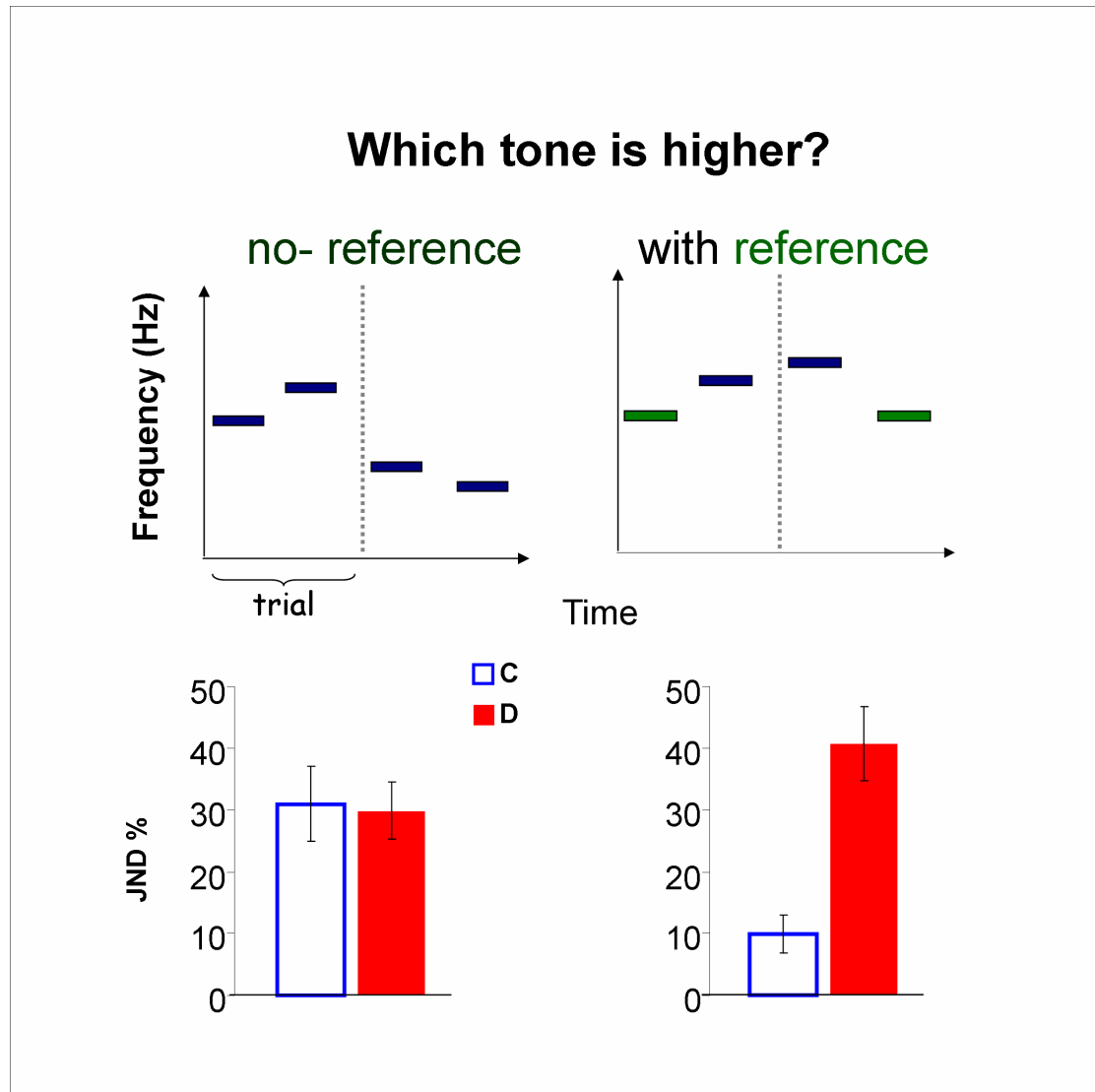


Figure 3.

