The role of anchoring in auditory and speech perception in the general and in dyslexic populations

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Theoretical treatments of language, reading and their disorders are typically modular. They postulate that because individuals with (for instance) dyslexia are more impaired in their reading than in any other cognitive domain, the core deficit(s) should be traced back to a specific cognitive process that is critical for reading, but not for other functions (see Vellutino, Fletcher, Snowling, & Scanlon, 2004 for an example). Similarly, because children diagnosed with language deficits are often those who have more pronounced difficulties in specific aspects of language (e.g., syntax, phonology), explanations are sought in a particular linguistic domain. This view however fails to account for findings that pure cases are rare and that individuals who fail to develop adequate reading also have deficits in other cognitive and perceptual domains. Thus, understanding domain specific deficits as part of a more general cognitive difficulty may provide a better characterization of the underlying mechanisms. Following this conceptualization, we propose that the difficulties experienced by individuals with dyslexia (often concurrent with broader language difficulties) across cognitive domains such as reading, working memory and perception can be explained as a result of a core, domain general difficulty in *anchoring*, namely impaired ability to implicitly detect the statistical regularities of environmental sounds.

In the following sections we list evidence for interrelations across cognitive domains that are typically studied in isolation – perception, reasoning and (working) memory. Subsequently we present anchoring as a putative mechanism that could account for these interrelations and provide evidence for its failure in dyslexia. We conclude by discussing the similarity between the concepts of "anchoring", "statistical learning" and "predictive coding".

Perception, reasoning and explicit working memory

Reasoning and language, the two hallmarks of human cognition, are closely related to the concept of working memory. Working memory is defined as the process/system responsible for the ability to perform manipulations (or computations) on information (items) that is temporarily held in short term memory (Baddeley, 1986). The number of such items is rather small, and is never larger than the 4-8 items that can be held in short term memory in one time. This limited capacity directly limits our ability to use a large number of items in our reasoning processes. Thus, for example, when attempting to deduce the series of rules governing the relationships between visually presented items (e.g., Raven's Matrices, Raven, Raven, & Court, 2000), individuals with a lager working memory capacity, will handle a larger number of examples or deduced rules and will thus be able to outperform individuals with lower working memory capacity (Carpenter, Just, & Shell, 1990). Similarly, reading and listening comprehension, are correlated with reading and listening spans. These spans are measured when individuals are presented with a sentence, asked to complete its final word and remember it, and then presented with another sentence etc'. Span is the total number of words they can recall (Daneman & Carpenter, 1980; Daneman & Merikle, 1996). One of the main characteristics of individuals with language and reading difficulties is poor verbal working memory (see Swanson, Zheng, & Jerman, 2009 for a recent meta analysis). However, the relations between poor verbal working memory and generally poor working memory (e.g. with simple sounds) was not systematically addressed.

Whereas working memory is now viewed as closely related to reasoning abilities (Gray, Chabris, & Braver, 2003; Jarrold & Towse, 2006; Kane & Engle, 2002), perceptual skills, particularly those that relate to resolution along simple physical dimensions (e.g., frequency discriminate between tones) are typically viewed as a separate low-level ability, implemented by a dedicated machinery (neuronal populations in sensory brain areas). Yet, the few studies that examined the statistical correlations between perceptual resolution and scores in tests of academic aptitude (e.g., SAT) or general intelligence found significant positive correlations (Deary, Bell, Bell, Campbell, & Fazal, 2004; Deary & Caryl, 1997; Raz & Willerman, 1985; Raz, Willerman, & Yama, 1987; Watson, 1991), consistent with the ideas put forth by Galton and Spearman more than a century ago. A potential functional linkage could be working memory. The conceptualization is similar. Like high-level reasoning tasks, discrimination tasks require holding items in memory (e.g. the representation of frequency of a tone), retaining them and then comparing them to subsequently presented items. In this case, the bottleneck may not be span (number of items) but perhaps accuracy of retention and comparison. Indeed, we found that both poorer perceptual scores and poorer scores in reasoning tasks are correlated with verbal working memory scores in the general population and among young adults with dyslexia (Banai & Ahissar, 2004). Specifically, participants who were less sensitive to small frequency differences in a 2-tone discrimination task ("which of the two sequentially presented tones is higher?") also had poorer reasoning skills as measured with the Raven's Matrices test (Figure 1, top left plot), and poorer working memory scores, as measured by the Digit Span backward test (Figure 1, top right plot), irrespective of whether they were poor or normal readers (filled versus empty bars). Note that these finding suggest that bottlenecks to auditory verbal and non-verbal working memory are shared.

Taken together, it therefore appears that working memory facilitates performance in a range of verbal and non-verbal tasks across cognitive domains (perception, reasoning, language). This raises the question of whether there is any way (or a separate meaning) for assessing reasoning (or perceptual) skills without the limitation embedded by our limited working memory. One conceptual approach is to apply measures that tax working memory to a different extent and examine whether they are differentially correlated to working memory. One such manipulation can be obtained by administering another standard non-verbal reasoning task – Block Design (Wechsler, 1997). In this task two dimensional geometric patterns should be recreated with colored blocks. Solution is typically not mediated by sequential accumulative verbalization (unlike the Raven Matrices task), but by matching each part separately. Intermediate successful steps are represented externally as the part of reconstruction (correctly placed blocks) that had been achieved. Therefore, successful previous steps need not be recalled internally. Indeed, in the group of dyslexics in which verbal working memory was highly correlated with Raven's cores, as illustrated in Figure 1, bottom left, performance in Block Design was not (Figure 1, bottom right). Both cognitive tasks are aimed to assess spatial reasoning, and while performance is indeed correlated in the general population, performance on these two tasks was not significantly correlated among dyslexic participants, suggesting that different bottlenecks governed performance in this group (Banai & Ahissar, 2004).

The finding that individuals with both language impairments (LI) and dyslexia also have auditory perceptual deficits is not new. Following the pioneering work of Tallal in the 1970s (Tallal & Piercy, 1973a, 1973b), it has been proposed that the language production and comprehension deficits of children with LI can be traced back to a general deficit in processing brief and rapidly changing auditory stimuli, which are characteristic of the structure of speech. Tallal (1980) later suggested that the same account could apply for dyslexia as well. Subsequent studies confirmed the presence of various auditory processing deficits among both children (e.g., Goswami et al., 2002; Heath, Hogben, & Clark, 1999; Lorenzi, Dumont, & Fullgrabe, 2000; McArthur & Hogben, 2001; Reed, 1989; Talcott et al., 2003; Walker, Hall, Klein, & Phillips, 2006) and adults (e.g., Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; McAnally & Stein, 1996; Ramus et al., 2003; Stoodley, Hill, Stein, & Bishop, 2006; Witton, Stein, Stoodley, Rosner, & Talcott, 2002) with dyslexia, but showed that those deficits were not confined to the processing of brief and rapidly presented stimuli (Ahissar, Protopapas, Reid, & Merzenich, 2000). In fact, it turned out that the profile of auditory deficits is such that it can not be attributed to any specific low level mechanism in the auditory system (Amitay, Ahissar, & Nelken, 2002). On the other hand, we found that the individuals with the poorest performance on our battery of perceptual tasks had particularly poor verbal working memory skills, that is they had substantial difficulties remembering verbal information while performing cognitive operations on that information, and poorer performance in cognitive tasks that are taxing for working memory (Banai & Ahissar, 2004).

Our finding that poor perceptual performance is clustered with poor verbal working memory can be explained by several potential impairments like poor executive functions, poor retention, or poor stimulus processing. For example, a comparison of two stimuli, which one is often asked to do in simple perceptual tasks, 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 (comparison and retention) 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 2^{nd} or the 3^{rd} stimulus was identical to the 1^{st}. This task had a higher memory load. We administered these 2 tasks both with both simple tones and with complex speech signals (Banai & Ahissar, 2006) (see Figure 2). 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, 13-14 year old dyslexics performed the easy task (Figure 2, left column) as well as a comparison group comprised of their non reading-disabled peers. On the other hand, regardless of the stimulus, dyslexics were significantly poorer on the more working memory demanding task (Figure

2, right column). These findings suggest that poor working memory skills impaired dyslexics' performance in simple auditory tasks.

We have thus claimed that working memory is related to both perceptual and reasoning skills, and that verbal working memory is correlated with non-verbal auditory memory. Following this logic we trained teenagers with poor reading abilities (and poor verbal working memory) on a series of 2-tone discrimination tasks ("which tone is higher? Longer?) (Banai & Ahissar, 2009). Following several weeks of training and substantial improvement on the trained tasks, we assessed transfer to verbal tasks. We found that both speech discrimination and verbal working memory skills improved. Moreover, the degree of working memory improvement was highly correlated with the amount of improvement obtained in 2-tone frequency discrimination, which was the first trained task (Banai & Ahissar, 2009).

Working memory – implicit components

The working memory tasks we discussed above are explicit in the sense that individuals consciously retain and manipulate the information. Indeed, traditionally, the concept of working memory specifically addressed explicit retention. Being intentional was an important aspect. For example, the limited capacity of verbal working memory was explained in Baddeley's popular model for working memory (Baddeley, 1986, 1996), by its decay within 2-3 seconds unless explicitly re-activated (by intentional rehearsal). However, the segregation to short-term, i.e. within 3 seconds, versus long term, leaves an important temporal range during which recent encounters are much more effective than long term experiences. Baddeley noted that in order to understand a situation, like a story or a conversation, individuals need to have longer spans, even though implicit. He termed this aspect "an episodic buffer" (Baddeley, 2000), i.e. an additional form of memory with a temporal range of episodes. We propose that some form of implicit memory, namely retention which is not intentional, is crucial not only for comprehension of events but for any form of perception on the one hand and reasoning on the other hand. This "contextual memory" retains important aspects of recently presented stimuli. It is within this range that anchoring, i.e. benefiting from recent experiences which are beyond the time and capacity ranges of explicit working memory, takes place.

Anchoring is a basic biological mechanism. Some form of implicit memory is retained whether called for or not, even in simple perceptual assessments under laboratory conditions. Thus, when asked to compare two basic stimuli, the exact strategy that is used and the resulting resolution crucially depends on recent history with similar stimuli. In the common protocol used to assess frequency resolution (and other dimensions) assessment is based on a series of trials. On each trial listeners are asked to reply which of two tones is higher, but tone pairs across trials are not independently chosen. In the typical case, one of the two tones is a reference (i.e. fixed across trials) and the non reference (presented either first or second) is always higher (or longer in a duration discrimination task). While common analysis assumes an actual comparison between the two stimuli in each trial and introspective reports by listeners are in line with this view, this is not the implicit strategy chosen.

Over 60 years ago, Harris (1948) showed that performance significantly improves under conditions in which a single reference tone is consistently repeated during each trial of the assessment as opposed to when on each trial the two stimuli are randomly selected, a phenomenon he attributed to psychological or perceptual "anchoring". More recently, we have extended Harris's findings showing the specific conditions under which listeners can anchor to and benefit from cross trial repetitions (Nahum, Daikhin, Lubin, Cohen, & Ahissar, 2010). We found that temporal consistency within a trial plays an important role. Thus when the first tone in each pair is fixed and the 2nd tone is either higher or lower, best frequency resolution is achieved (Figure 3, left panel, leftmost bar). Interestingly, the reference tone need not be explicitly presented. Similar thresholds are obtained when the reference tone is presented once at the beginning of the assessment and each subsequent trial contains only one tone (higher or lower, than this reference, with equal probability). Listeners are asked whether it is lower or higher than the initially presented reference tone (Figure 3, left panel, green bar). Temporal consistency can be used also when the repeated reference is presented 2nd (rather than 1st) (Figure 3, left panel, red bar), though thresholds are not as robust and some individuals have difficulties in attaining accurate performance under these conditions. Thus in all protocols in which a reference is present either explicitly or implicitly, thresholds are lower (better) compared to a condition in which there was no reference at all (Figure 3, left panel, black bar).

We used ERPs recorded during task performance to assess implicit strategies that are associated with successful anchoring. Listeners performed the 2-tone frequency discrimination with a reference always 1st or, in separate assessments, with the reference consistently presented 2nd. We used a well studied ERP component, P3, which reflects an implicit perceptual categorization, to decipher the timing of an implicit decision within a trial. As shown in Figure 3 (right panel), P3 followed the non-reference tone, namely the 2nd tone when the reference was always first and the first tone and the reference was presented second. This means that successful listeners did not wait for the second tone in the pair in order to make the 2-tone discrimination! Rather, they used previous references as an internal anchor. This means that rather than using explicit memory mechanisms for comparing the two tones within a trial, they used implicit memory mechanisms whereby previous tones, which were not intentionally memorized, served as an internal reference. Listeners implicitly classified the non reference tone in each trial as higher or lower from their anchored reference. These findings indicate that assessment protocols that allow our perceptual system to replace inter-stimulus comparisons with classification of a single stimulus relative to an internal representation (of the reference) yield optimal performance. The classification procedure however is disrupted by inconsistency in the temporal location of the reference, forcing listeners to resort to the more difficult 'retain and compare' strategy, based on mechanisms of explicit memory (Nahum et al., 2010).

Initially poor performers have a difficulty in using anchoring. It seems like some aspect of the reference representation has to be improved with practice so that effective anchoring can take place (Nahum et al., 2010). This observation may explain the benefits obtained by the dyslexic adolescents we trained (Banai & Ahissar, 2009). Training may have generalized to an explicit working memory task, because trained participants may have learned to implicitly create more stable representations of the stimuli that were recently used in this task, thus freeing higher level explicit working memory resources to perform the actual re-ordering operation required by the digit backwards task.

The implicit formation of internal representations (anchoring) can also be interpreted as an implicit memory process. Such a process may serve to boost the relatively small capacity of explicit working memory by allowing individuals to form predictions based on past events. It should be noted however that this process is completely implicit because even highly trained listeners (who benefit from anchoring at least to a similar extent) were unaware of the temporal position of the reference and reported that they performed a two tone comparison in every trial (Nahum et al., 2010).

Anchoring and perception in dyslexia

As described above, dyslexic individuals have difficulties in verbal and non-verbal explicit auditory working memory tasks. Moreover, these difficulties are observed already at a young age (Reed, 1989) and their degree is correlated with the degree of difficulties in decoding the alphabetical script (Ahissar et al., 2000; Ben-Yehudah, Banai, & Ahissar, 2004; Talcott et al., 2002; Witton et al., 1998). However, as suggested above, difficulties in explicit working memory can result from impaired implicit anchoring mechanisms. In this section we shall describe the evidence that dyslexics suffer from generally poor anchoring ability in the auditory modality (Ahissar, 2007; Ahissar, Lubin, Putter-Katz, & Banai, 2006).

In order to distinguish between the deficient anchoring and the deficient comparison alternatives, i.e. deficient implicit versus deficient explicit working memory, we (Ahissar et al., 2006) administered two versions of the 2-tone discrimination task – the one we used in our 2004 study in which a repeated reference appeared on every trial (1st or 2nd), and a *no-reference* version of the same task (similar to the one used by Nahum et al., 2010). Since the *no-reference* paradigm contained no fixed reference tone, anchoring to a reference was not useful and on-line comparison of the two stimuli was the efficient strategy. We reasoned that if dyslexics' impairment resides in the comparison process, their relative difficulty will increase in the more difficult, higher threshold, no-reference paradigm. However, if their deficit resides in the formation of the internal representation and the ability to switch from comparison to implicit classification, as described above for the general population, their relative difficulties will be greater with the standard, reference containing protocol. The findings (illustrated in Figure 4) were clear. Performance of 7th grade dyslexic participants did not differ from that of their peer group in the difficult, comparison requiring, *no-reference* paradigm. However, in contrast to the peer comparison group, dyslexics' performance did not improve when the same reference was repeated across trials, indicating that dyslexics' ability to construct and utilize the reference as an internal anchor is impaired. Thus, dyslexic individuals fail to use the anchoring mechanisms that allow their peers to use an automatic classification process that is based on the implicit memory of recently presented stimuli. Consequently, they have to rely more on explicit comparisons.

Dyslexics often suffer from increased sensitivity to noisy environments. Several studies (Boets, Ghesquiere, van Wieringen, & Wouters, 2007; Boets, Wouters, van Wieringen, & Ghesquiere, 2007; Ziegler, Pech-Georgel, George, & Lorenzi, 2009) reported poor speech perception in noise. To assess whether the difficulties dyslexics have in speech perception in noise can be attributed to deficient anchoring mechanisms, we administered a pseudoword repetition task with a either a small (10 words) or a large (40 words) vocabulary (Ahissar et al., 2006). Under the first condition each word repeated quite a few times, whereas with the large set no word was repeated more than twice. Thresholds for speech perception in noise under the large vocabulary did not differ between dyslexics and their non reading impaired peers. On the other hand, when the small set was used, dyslexics performed significantly worse than controls. This finding suggests that similar anchoring processes govern speech discrimination and 2-tone discrimination, and that dyslexics' anchoring impairments limit their resolution in both.

Further evidence for dyslexics' impaired implicit processes comes from studies of ERP measuring the MMN component. 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). MMN is elicited automatically and can be recorded when participants are busy in other activities. Detecting the oddball requires formation of a stimulus-specific memory trace (anchor) for the repeated standard. Several studies reported reduced MMN responses to frequency and to phonetic deviants among individuals with dyslexia and language disability (Kraus et al., 1996; Kujala, Belitz, Tervaniemi, & Naatanen, 2003; Kujala, Lovio, Lepisto, Laasonen, & Naatanen, 2006; Lachmann, Berti, Kujala, & Schroger, 2005; Maurer, Bucher, Brem, & Brandeis, 2003; Schulte-Korne, Deimel, Bartling, & Remschmidt, 2001; Sharma et al., 2006; Stoodley, Hill et al., 2006), although results are mixed, probably due to MMN having a small signal to noise ratio and to the relatively small populations tested in each study (Bishop, 2007). Interestingly, the proportion of studies that found reduced sensitivity to frequency deviances is larger than those that found reduced sensitivity to phonetic contrasts.

The effects of stimulus context and in particular the sensitivity to the consistency of the auditory environment may not be limited to the cortex. When brainstem encoding of speech syllables was measured in both repetitive and variable contexts, typically developing children encoded the pitch related properties of the acoustic signal more robustly in the repetitive context, and the degree of this context facilitation correlated positively with their ability to perceive speech in noisy environmental conditions

(Chandrasekaran, Hornickel, Skoe, Nicol, & Kraus, 2009). In line with the anchoring deficit hypothesis, these context effects were significantly reduced among children with dyslexia. These findings suggest that context consistency can improve the accuracy of sound encoding even at low level auditory areas that are considered sensory or pre-cognitive, thus influencing the input into higher level areas.

Anchoring, statistical learning and predictive coding – between perception and cognition

We have presented evidence that normal anchoring mechanisms, which allow most individuals to benefit from the statistics that characterize each episode or context, are malfunctioning in dyslexia and that this malfunction can account for dyslexics' difficulties in discriminating both simple tones and speech elements. Our examples of anchoring, i.e. performing better with repeated stimuli, could be viewed as simple cases of statistical learning. Namely, sensitivity to increased probability of a specific stimulus is an important aspect of statistical learning, i.e. learning the statistical regularities that characterize a specific context.

Long term implicit statistical learning is crucial in almost every situation (Fiser & Aslin, 2001; Perruchet & Pacton, 2006; Saffran, Johnson, Aslin, & Newport, 1999). For example, an important aspect of language acquisition is learning the statistical regularities that characterize the structure of this language (both at the phonological and the syntactical levels) (Saffran, 2003). There is ample evidence that the distributional frequency of phonemes (called phonotactic probability) influences multiple aspects of language processing throughout life span (see Auer & Luce, 2005 for review), and it has even been suggested that sensitivity to these probabilities underlies infants' implicit learning of word boundaries in spoken language (Saffran, Aslin, & Newport, 1996). At the physiological level, it has been shown that in the general population, both young adults (Bonte, Mitterer, Zellagui, Poelmans, & Blomert, 2005) and children (Bonte, Poelmans, & Blomert, 2007), are sensitive to phonotactic probabilities. Namely, an MMN response, induced by oddball stimuli, is produced in response to a rare phonotactic combination embedded in a context of a more frequent combination. This sensitivity was not observed in children with dyslexia whose MMNs were unaffected by the phonotactic probability of the deviant (Bonte et al., 2007). Bonte and colleagues interpreted these findings as reflecting a deficit in the pre-lexical, phonetic-phonological processing of speech in dyslexia which could influence children's ability to match phonological and orthographic representations of speech sounds during the early stages of reading acquisition.

The examples from language typically do not dissociate between short term processes of statistical learning and the ability to acquire long term representations. Sensitivity to the regularities of a given context probably requires adequate long term representations. Thus we are not sensitive to regularities which we do not have the machinery to detect. However, adequate long term representations do not necessarily guarantee adequate anchoring. Thus, having shown that fast anchoring processes are impaired in dyslexia does not necessarily mean that phonological representations are impaired. Whether basic phonological representations are indeed impaired, as traditionally claimed (e.g., Boada & Pennington, 2006; Snowling, 2000) or are not impaired but are not accessed efficiently due to the reduced anchoring benefit in dyslexia (Ramus & Szenkovits, 2008) remains a question for future research.

Another question raised by our findings is the extent of poor anchoring. We have shown that it is not specific to speech, and applies to other sounds in a similar manner. But does it apply to visual and motor anchoring abilities too? Namely, is statistical learning in dyslexia impaired in a more general manner? Some studies suggest that this is the case at least for some sub-populations of dyslexics who have difficulties in the implicit learning of visual or motor sequences (Howard, Howard, Japikse, & Eden, 2006; Stoodley, Harrison, & Stein, 2006; Stoodley, Ray, Jack, & Stein, 2008; Vicari et al., 2005; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003), or categories (Sperling, Lu, & Manis, 2004).

The repeated finding that, in the general population, predictions based on the context of recently presented stimuli are automatically and implicitly generated, is consistent with the idea of predictive coding, an earlier version of which was already postulated by Helmholtz in the 19th century (termed implicit inferences). Recently specific neuronal implementations were proposed (e.g., Friston, 2005). The basic concept is that incoming stimuli are compared with high-level produced predictions. If they do not match, higher level predictions are modified and updated. In these terms, deficient anchoring, as we have shown in dyslexia, could stem from less efficient/accurate construction of predictions by higher levels or by ineffective comparison and updating mechanisms.

The concepts of anchoring and predictive coding dissolve the traditional modular views of separate perceptual versus cognitive processes (see Mesulam, 1998). Efficient anchoring improves the efficiency of both cognitive and perceptual processes by automatically producing effective predictions and thus eliminating the need for un necessary additional laborious computations, whether in comparing 2 sounds or in onlone multiplication of numbers. These ideas are also consistent with recent accounts of auditory (Fritz, Elhilali, David, & Shamma, 2007; Näätänen, Tervaniemi, Sussman, Paavilainen, & Winkler, 2001; Scheich, Brechmann, Brosch, Budinger, & Ohl, 2007) and visual (Bahrami, Lavie, & Rees, 2007; Pasternak & Greenlee, 2005) cortices, as intelligent in the sense that they participate in implicit inferences and contribute to efficient decision making at various levels.

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Figure legends

Figure 1. The relationships between perception, reasoning and working memory. Top: Individuals with better perceptual resolution (assessed with a frequency discrimination task) scored higher on Raven Matrices (left) and had larger working memory spans (assessed with Digits Backwards, right). Empty bars – normal readers, filled bars – poor readers. Error bars are ± standard error of the mean (sem). Bottom: Correlations between working memory (Digit Backwards spans) and two cognitive tasks differing in the degree of working memory load – Raven's Matrices (left) and Block Design (right). Adapted from Banai and Ahissar (2004).

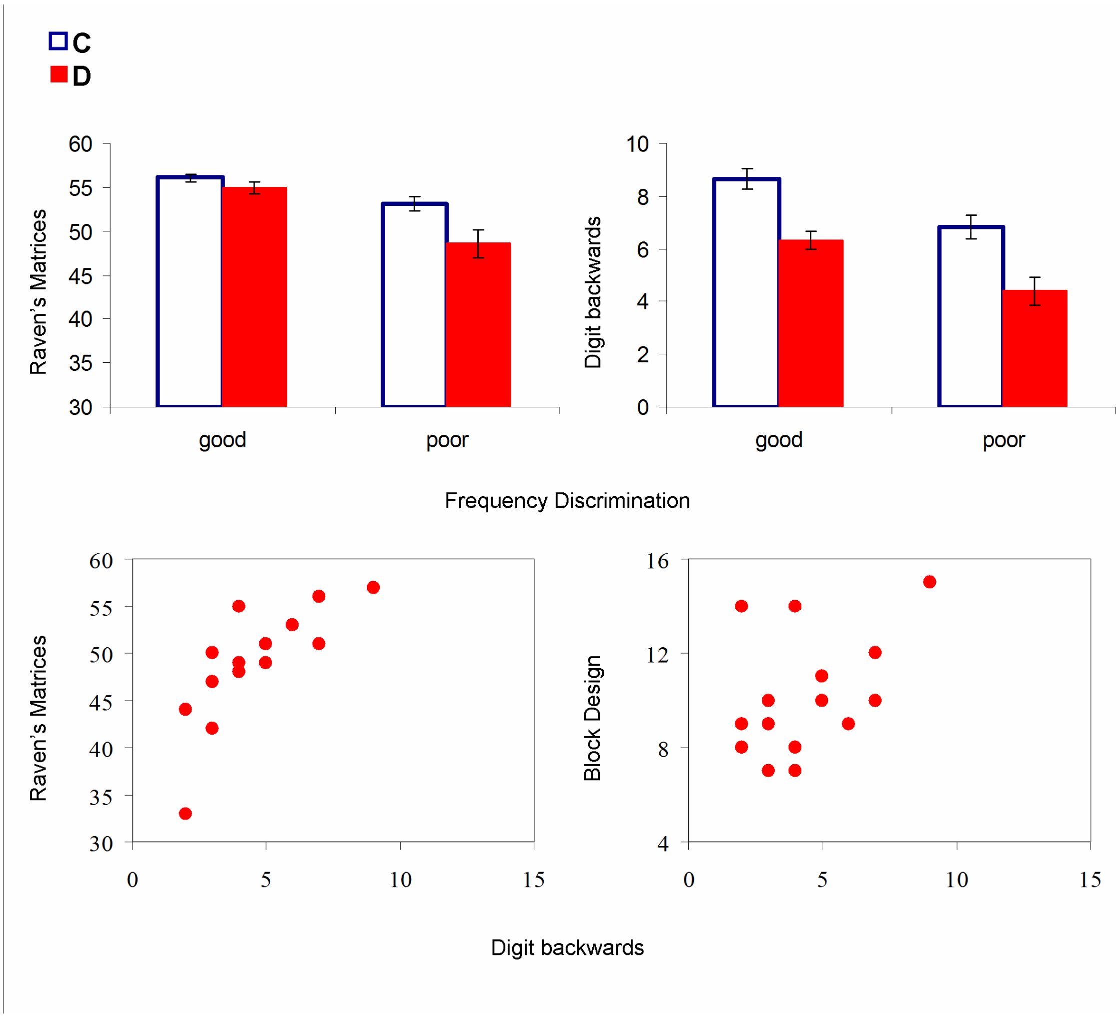
Figure 2. Assessing the respective roles of working memory load and stimulus complexity. The figure shows average results of dyslexics (D) and their age matched comparison group (C) under the four conditions. Increasing the demands of stimulus retention and comparison (right versus left column) significantly 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. Reprinted from Trends in Cognitive Science, 11, Ahissar M., Dyslexia and the anchoring deficit hypothesis (2007), with permission from Elsevier.

Figure 3. The anchoring benefit and the role of the reference. Left panel. Frequency discrimination thresholds as a function of reference consistency. Left to right: reference presented as the first tone on each trial (blue bar), as the second tone on each trial (red bar), at the beginning of the block only (green bar), no reference at all (black bar). Right panel. ERP waves (group averages) recorded while participants performed the 2-tone

frequency discrimination task with a fixed reference appearing either first (blue trace) or, in a separate block of trials, second (red trace). Adapted from Nahum et al., 2010.

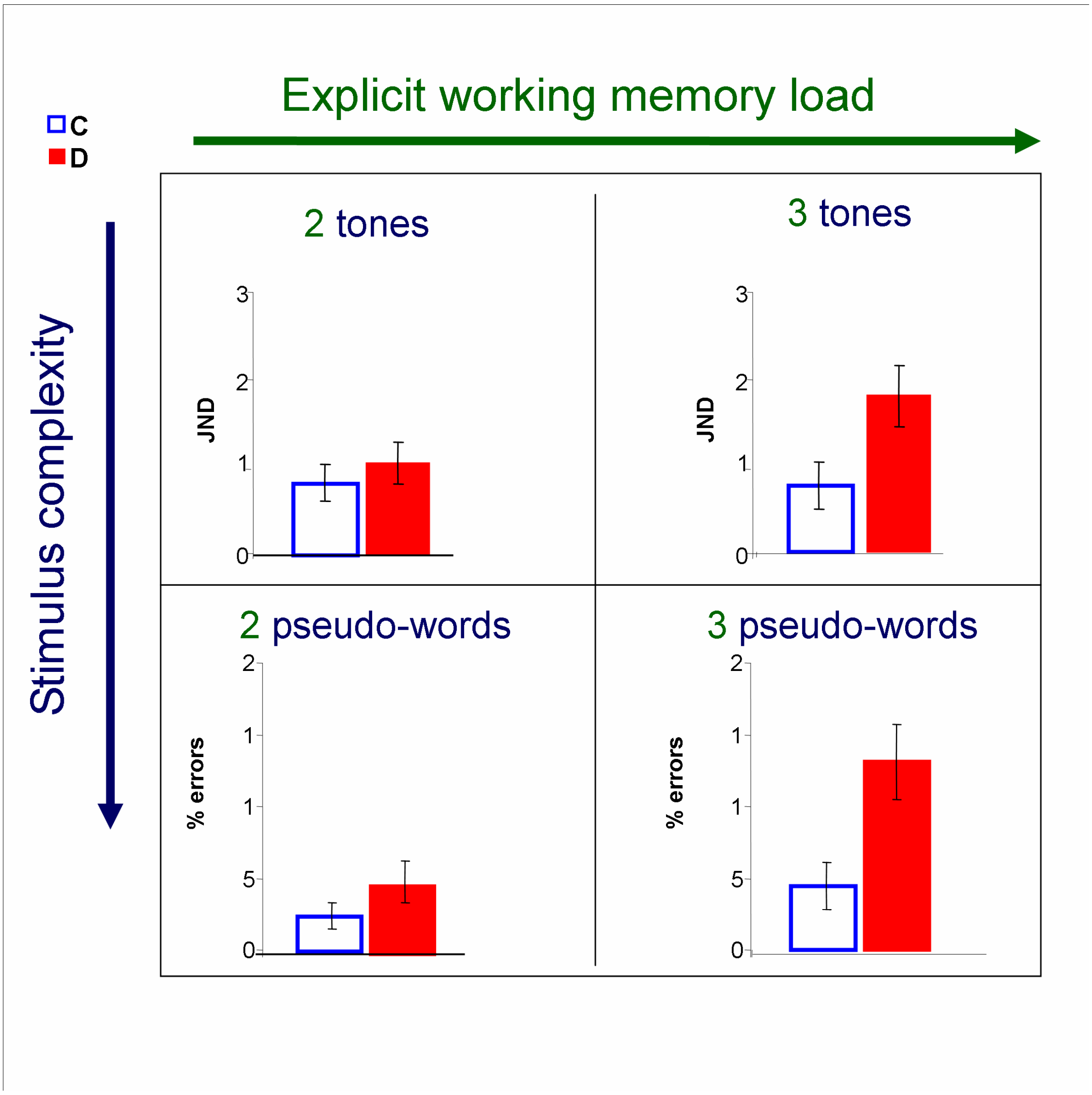
Figure 4. **The failure to anchor to the reference stimulus in dyslexia.** Top: A schematic illustration of single trials in the no-reference (left) and reference (right) frequency discrimination paradigms. Bottom: Average frequency just noticeable differences (±1s.e.m) of the dyslexic (D, red) and comparison (C, blue) groups in the no-reference (left) and reference (right) tasks. Reprinted from Trends in Cognitive Science, 11, Ahissar M., Dyslexia and the anchoring deficit hypothesis (2007), with permission from Elsevier.

Figure 1.



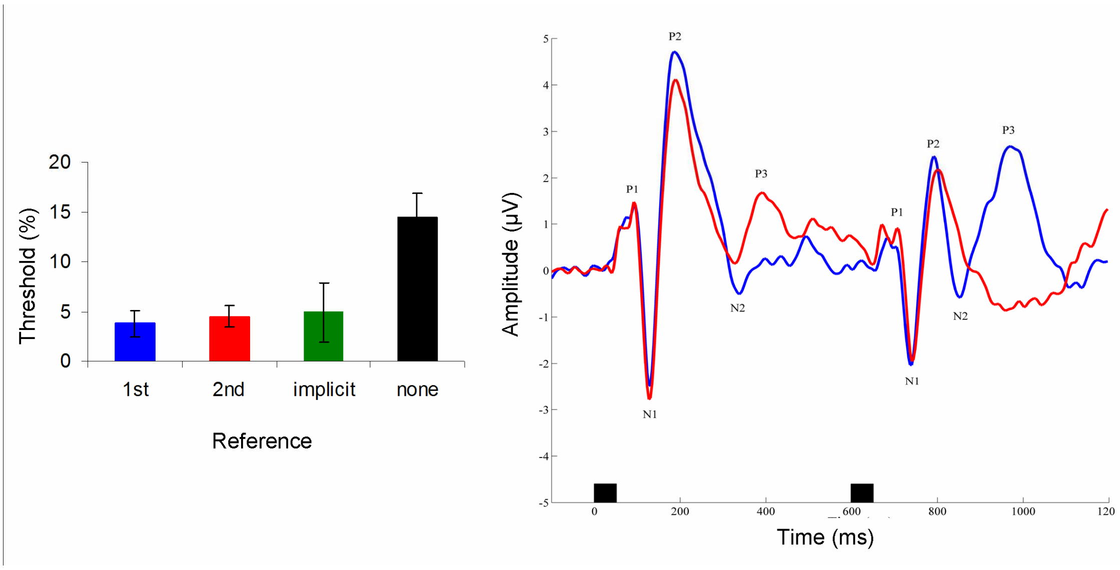
C
D
Raven's Matrices
60
55
50
45
40
35
30
good
poor
Digit backwards
10
8
6
4
2
0
good
poor
Frequency Discrimination
Raven's Matrices
Block Design
16
12
8
4
0
5
10
15
Digit backwards

Figure 2.



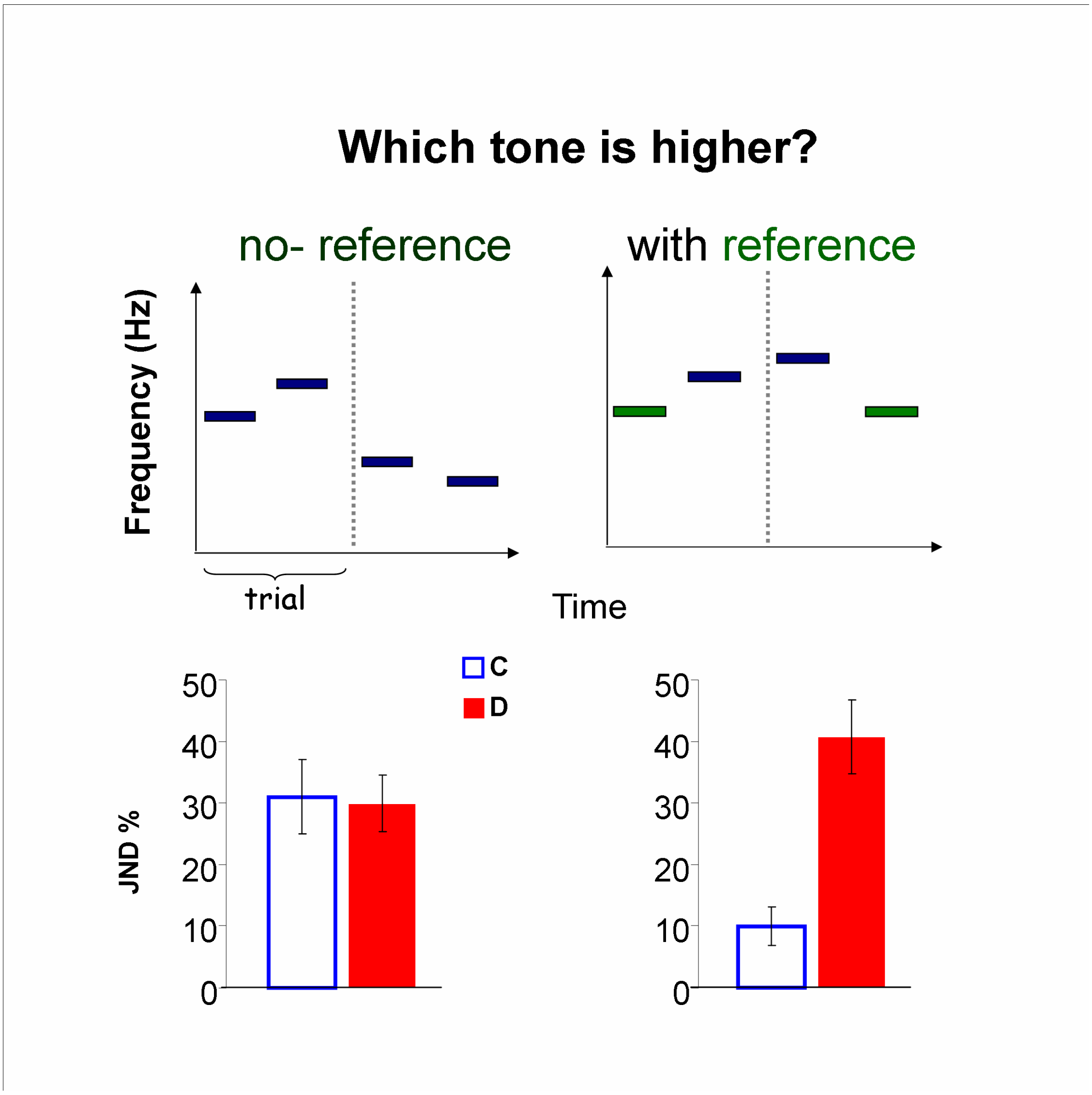
C
D
Explicit working memory load
Stimulus complexity
2 tones
3 tones
JND
3
2
1
0
2 pseudo-words
3 pseudo-words
% errors
2
1
1
5
0

Figure 3.



Threshold (%)
20
15
10
5
0
1st
2nd
implicit
none
Reference
Amplitude (µV)
5
4
3
2
1
0
-1
-2
-3
-4
-5
P1
P2
N1
N2
P3
P1
P2
N1
N2
P3
0
200
400
600
800
1000
120
Time (ms)

Figure 4.



Which tone is higher?
no- reference
with reference
Frequency (Hz)
trial
Time
C
D
JND %
50
40
30
20
10
0
50
40
30
20
10
0