Algorithms Based on Cognitive Neuroscience Designed to Aid Reading, Learning, and Navigation

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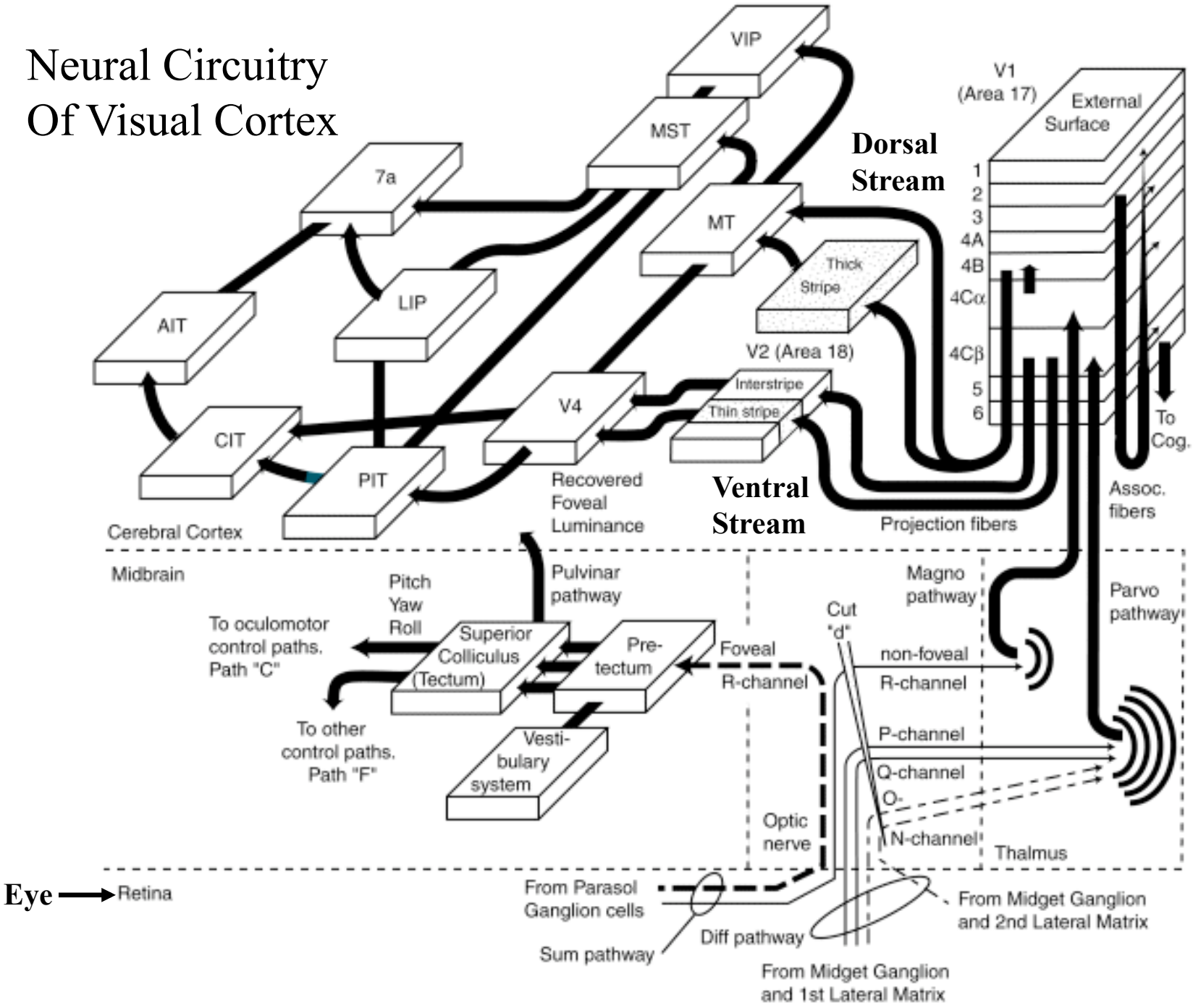
Background

- Algorithms based on cognitive neuroscience offer much promise for improving reading, learning, and automated navigation.

- Algorithms based on the development of cognitive functions such as reading and navigation enable using biological systems to guide adaptive learning systems.

Neural Circuitry Of Visual Cortex



Inefficient Readers Have Immature Motion Pathways To Discriminate Directionality Which Produces:

- Temporal and spatial sequencing problems.
  - Confusing b's and d's, and p's and q's
  - Confusing saw and was
  - Not seeing small words, like 'a', 'the', 'on', 'of' correctly, but longer words are not a problem
  - Seeing the words on the page move
  - Spelling and creative writing problems
  - Difficulty remembering a list of instructions
- Difficulty judging the direction and speed of moving objects.
- Reduced brain activity in the motion area.

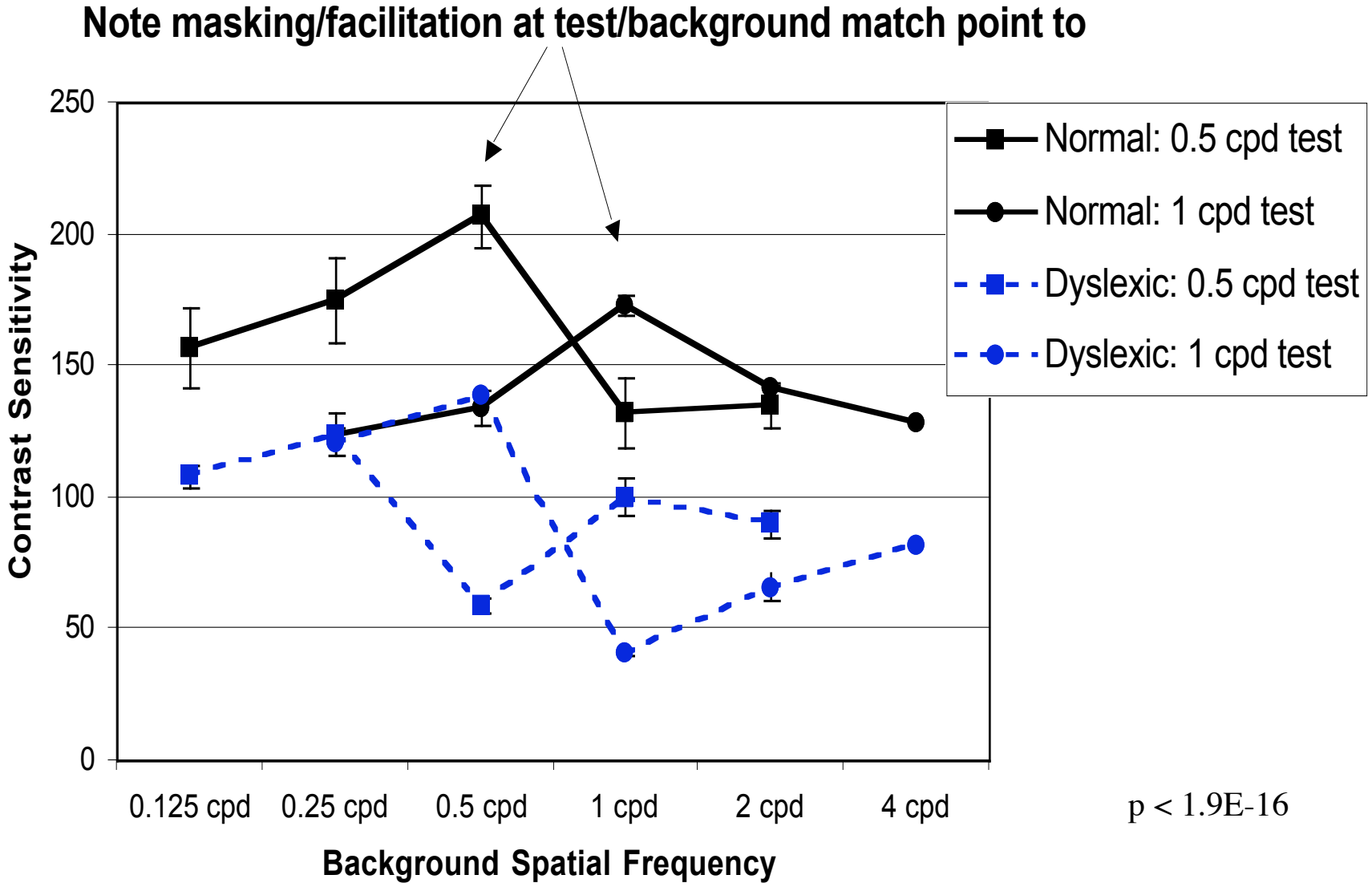
Evidence that Dyslexic Readers Have Immature Motion Networks

- Higher contrast thresholds and visible persistence to detect brief patterns.
- Temporal and spatial sequencing problems (confusing b's and d's, saw and was).
- Higher direction and velocity discrimination thresholds.
- Reduced fMRI responses in primary visual cortex & MT (cortical area specialized for motion).
- Unstable binocular control and depth localization.
- Anatomical and physiological anomalies of motion pathways that indicate lack of inhibitory networks.

PATH (Path T**o** R**eading**) Therapy

- Based on this new understanding, I have developed PATH therapy, a clinically proven program that addresses these deficits.
- This program, administered with the use of a personal computer, provides a comprehensive, rapid, and effective regimen for remediating reading problems that has been used successfully on over 900 students in 7 different public elementary schools over the past several years.
- **Problem readers show a *one to three grade level improvement*** in reading fluency **after only fifteen weeks of using this program**.

Direction Discrimination Reveals Two Types of Readers



$p < 1.9E\text{-}16$

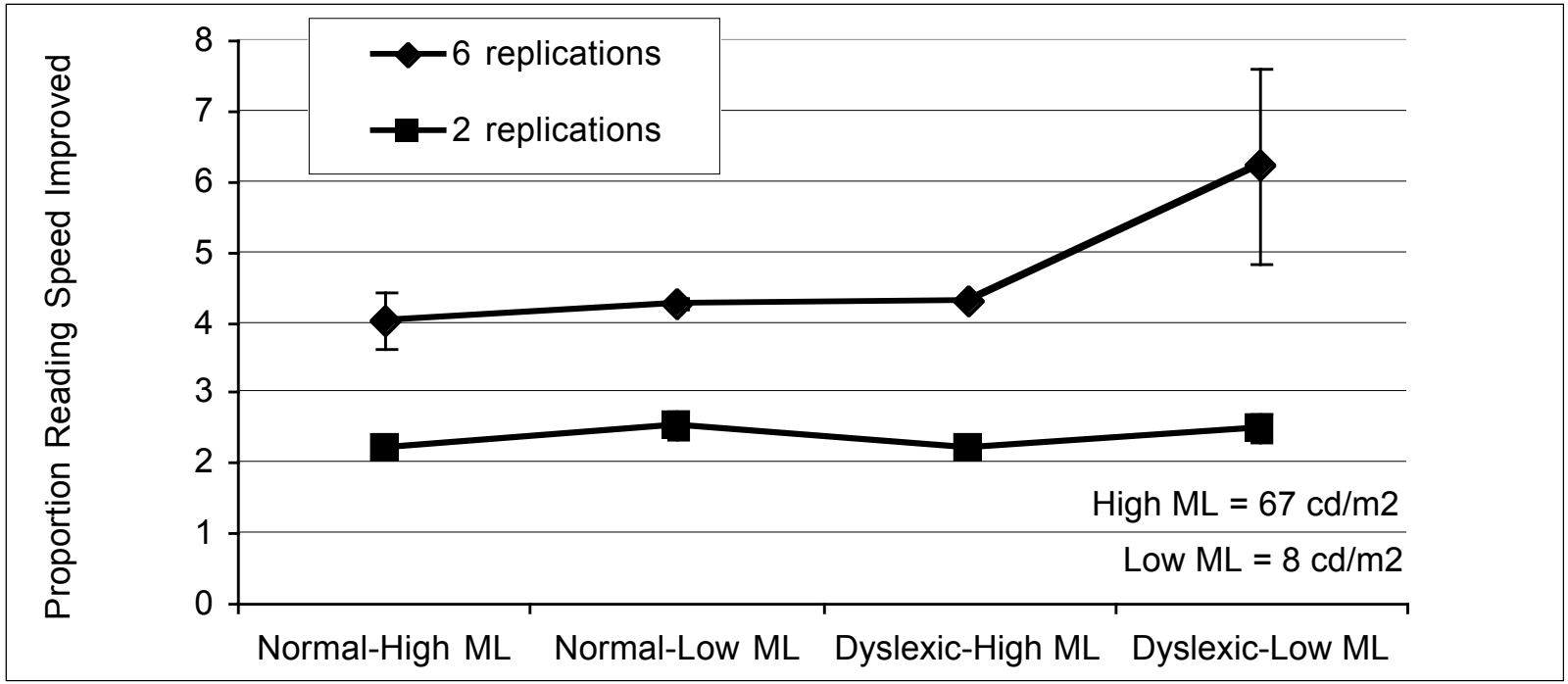
Training Motion Pathways

- If inefficient readers (from slow readers to dyslexics) have immature motion pathways, then strengthening the motion pathways should improve reading.

- Left-right movement discrimination for sine-wave gratings, on a grating background critically involves motion pathways at both low and high levels of processing.

- Previous results found that training on direction discrimination significantly improved reading speed.

Direction Discrimination Training Improved Reading Speeds



$p < 0.0003$

How Training Motion Discrimination Improves Reading Skills

- Propose works by tuning up one of the major visual pathways, the *'where'* or motion pathway (dorsal stream) that people use to locate patterns and objects.

  [Normally the *'where'* pathway signals the presence of an object to guide the *'what'* *or* pattern pathway (ventral stream). In children with reading problems, however, the *'where'* and *'what'* pathways seem to signal the brain at the same time, so that the *'what'* pathway does not know where to look.]

- Enables breaking camouflage to more distinctly see: 1) the word being read in the sea of words on the page, and 2) the letters in each word.

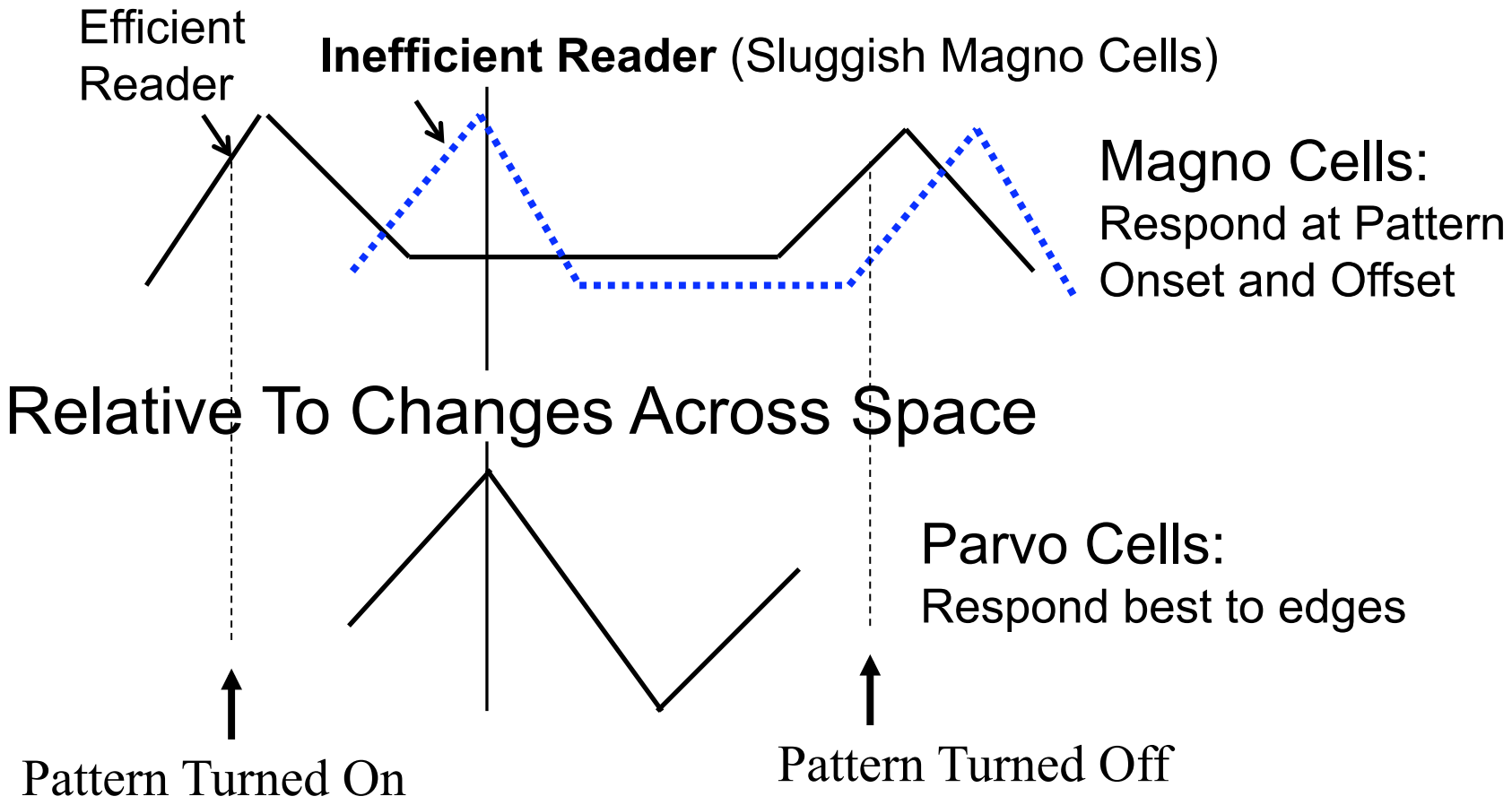
Most Probable Mechanism that is Involved in Direction Discrimination Being Linked to Reading

- Even though the timing of visual events in the direction selectivity network is provided by motion-sensitive cells, the background frame of reference is provided by pattern-sensitive cells in the primary visual cortex.

- The ability of magnocellular neurons to bracket the activity of linked parvocellular neurons over time is what has been disrupted in dyslexia (inefficient readers), resulting in timing deficits that cause temporal and spatial sequencing deficits, and slow reading speeds.

Direction Selectivity (De Valois *et. al.* 2000)

Signaled By Changes Over Time



Methods

- QuickTime movies were used to train students
- Participation: **Study 1**: 75 Efficient Readers (ER), 35 Inefficient Readers (IR) in grade 2; **Study 2**: 65 ER and 41 IR in grades 2 and 3
  - Study 1: Most IR (dyslexics) were dyseidetic (22), 6 dysphonetic, 4 mixed
  - Study 2: Most IR (dyslexics) were dysphonetic (28), 1 dyseidetic, 12 mixed
- Standardized literacy tests and reading speed were measured at beginning and end of study
- Treatment: Direction discrimination (PATH therapy) was trained once to twice a week either in computer lab or in individual classrooms
- Control 1: Computer game to train word discrimination was played either at the beginning or in the middle of the study
- Control 2: One group of students only had the school's regular reading program (At least 60 min directed reading)
- Second Study: Background complexity increased from single to multifrequency background gratings as training progressed

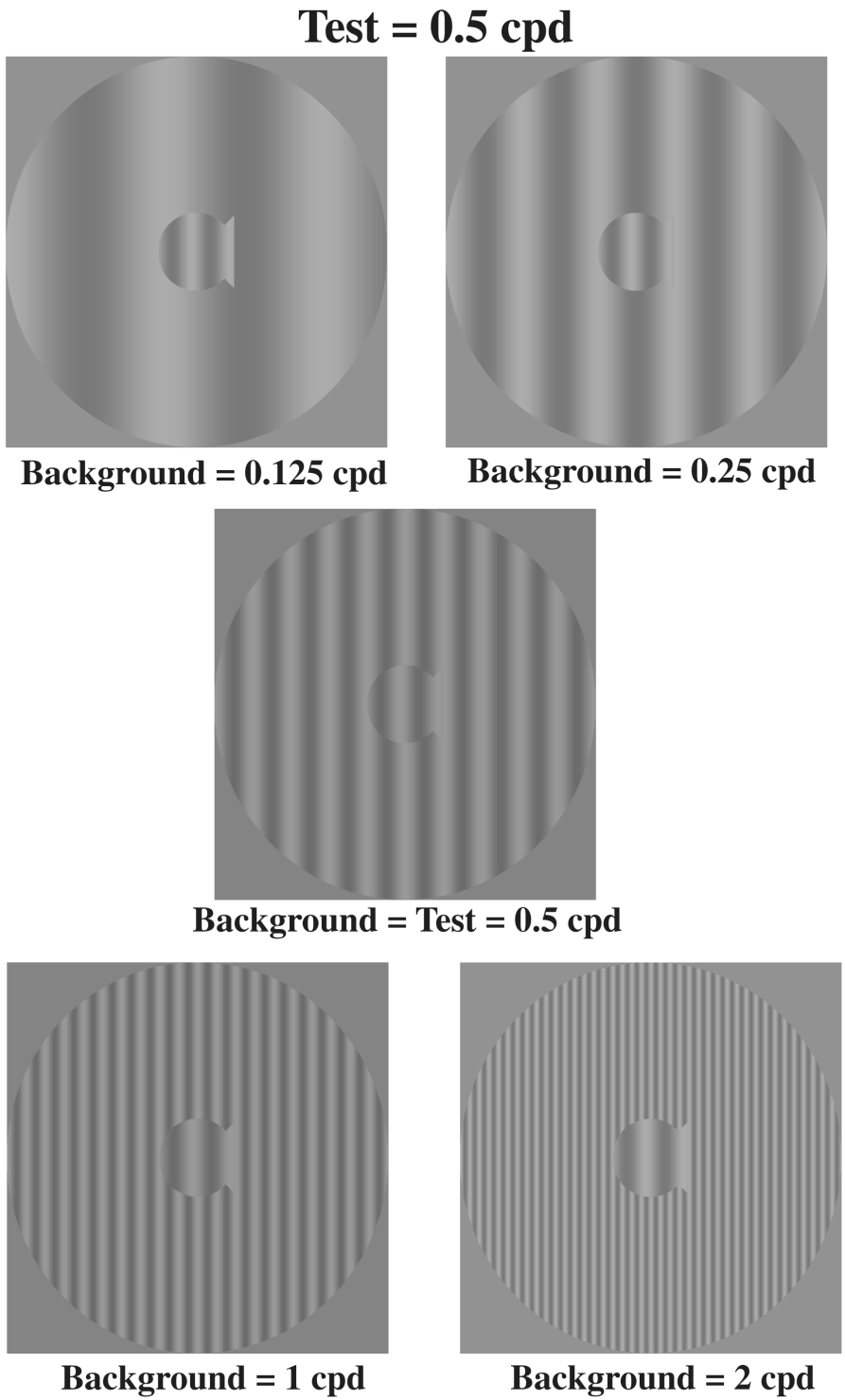


Fig. 1. Sample patterns for test frequency = 0.5 cyc/deg (cpd) on Different Backgrounds

Stimulus Patterns Designed To Activate Motion Sensitive Cells

- The stripes of the center test pattern move left or right 90 deg.
- The width of striped patterns on striped backgrounds and amount of movement are designed to activate motion sensitive cells maximally.
- Striped patterns activate motion pathways at both early (retinal and lgn) and later (cortical) processing levels.

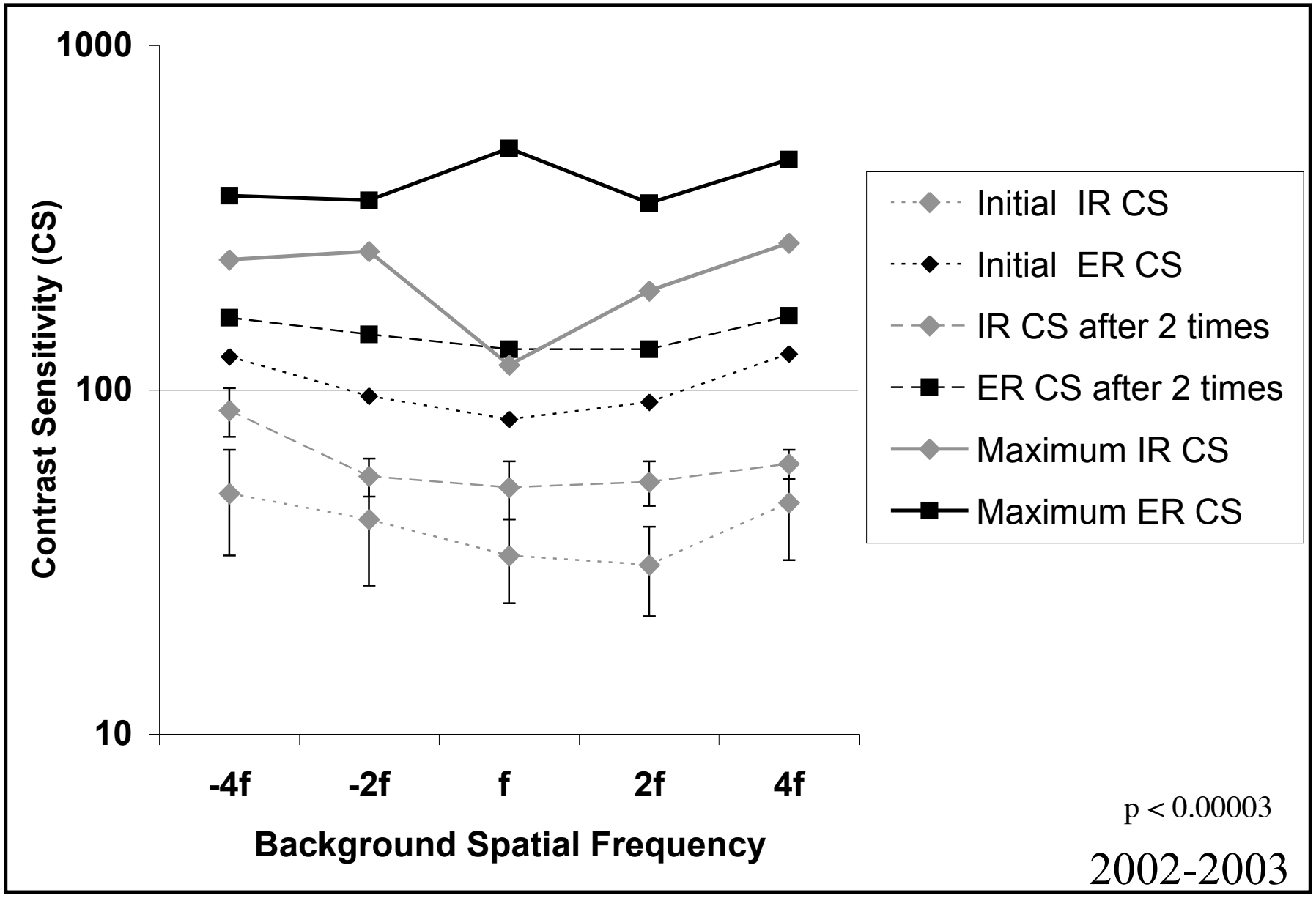
Mean value (either words/minute or initial grade level**) for each group on each reading skill, and the significance of the difference between inefficient and efficient readers.**

Reading Skill	**Inefficient Reader**	**Efficient Reader**	**Significance Level**
Fluency- Grade 2	150 ± 10 words/min	319 ± 24 words/min	$p < 0.00000001$
Fluency- Grade 3	159 ± 12 words/min	333 ± 15 words/min	$p < 0.00000007$
Word ID – Grade 2	2.7 ± 0.12	4.2 ± 0.2	$p < 0.00000001$
Word ID – Grade 3	3.3 ± 0.2	4.6 ± 0.2	$p < 0.0001$
Spelling – Grade 2	2.3 ± 0.1	3.8 ± 0.2	$p < 0.000000008$
Spelling – Grade 3	3.1 ± 0.2	5.0 ± 0.2	$p < 0.00000009$
Comprehension - Grade 2	1.1 ± 0.14	2.3 ± 0.17	$p < 0.00000008$
Comprehension - Grade 3	1.6 ± 0.14	2.9 ± 0.26	$p < 0.000006$

Contrast Sensitivity Function (CSF) for Direction-Selectivity

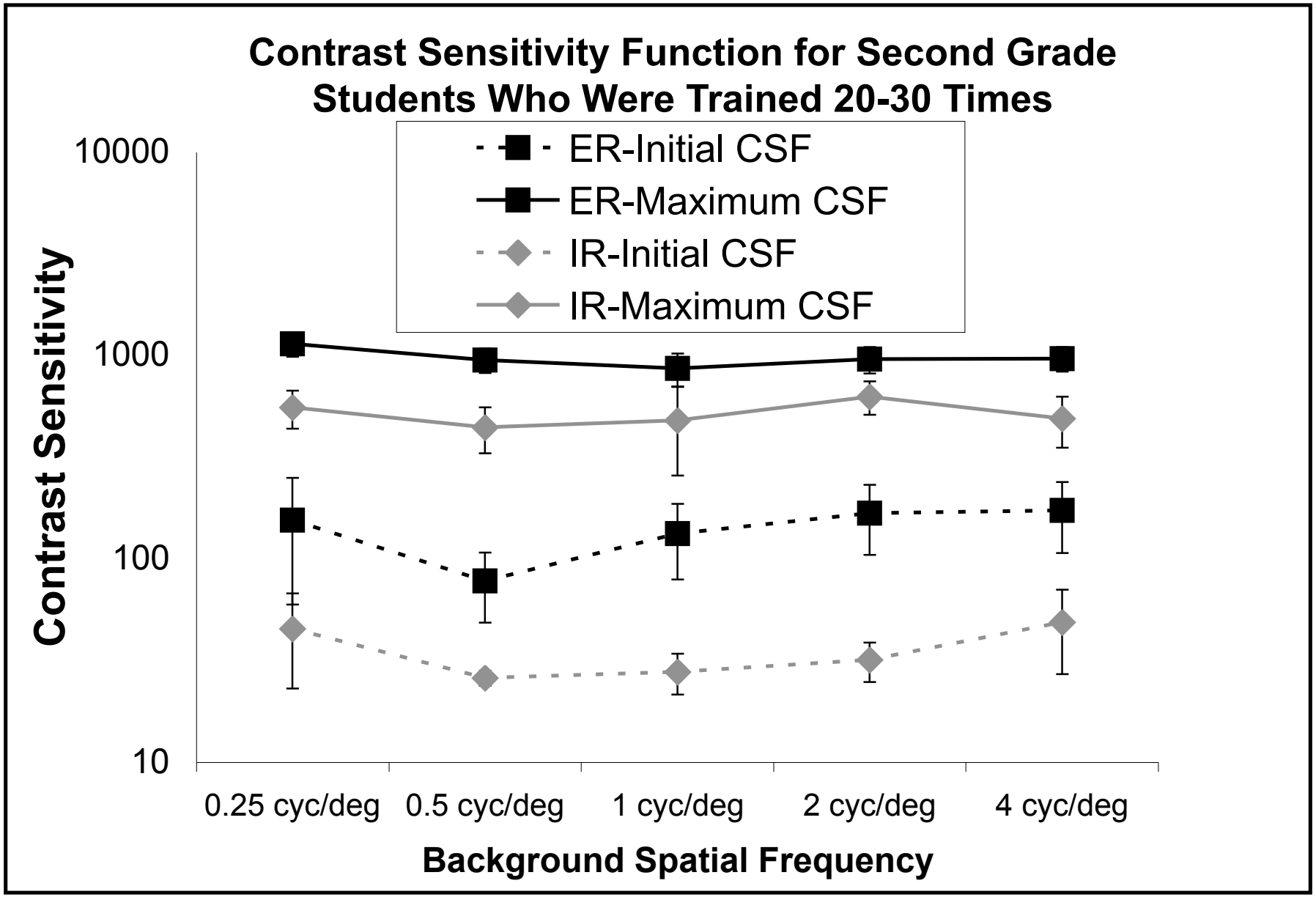
- Inefficient readers were three times less sensitive than were efficient readers when discriminating the direction of motion, significant at $p < 0.00003$.
- As the intervention training progressed over time, not only did the child's CSF for motion discrimination improve 3-4 fold, but the time taken to practice left-right movement discrimination was reduced in half (by second time practiced, PATH therapy completed in 7-8 minutes).
- Finding that following practice on left-right movement discrimination, inefficient readers had more perceptual learning shows that inefficient readers are attending to the task, strengthening the directionally-selective motion pathways, thereby improving all reading skills.

Contrast Sensitivity Function For Second Graders (NIH Study)

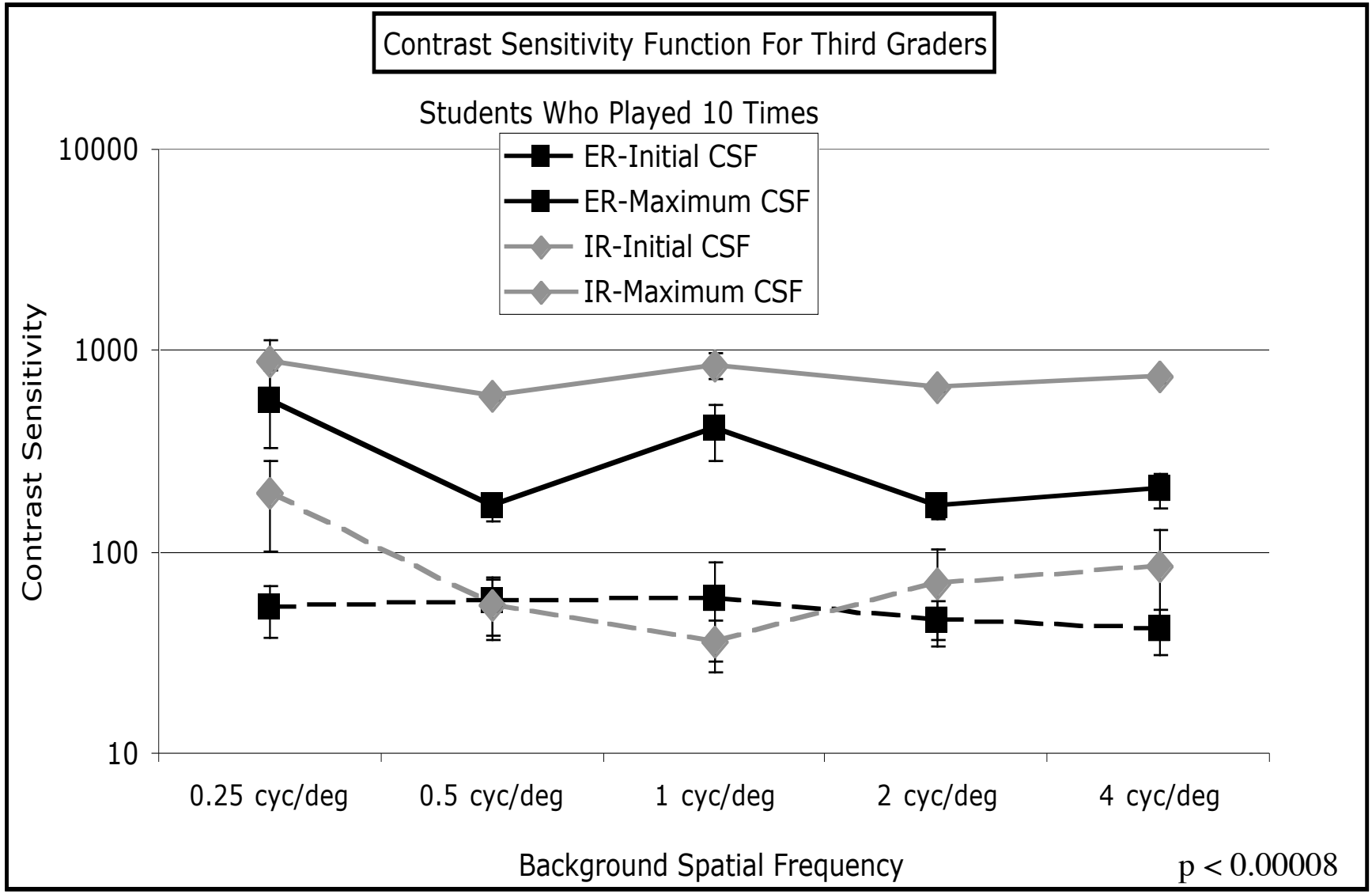


$p < 0.00003$

2002-2003


Contrast Sensitivity Function for Second Grade Students Who Were Trained 20-30 Times
ER-Initial CSF
ER-Maximum CSF
IR-Initial CSF
IR-Maximum CSF
10000
1000
100
10
Contrast Sensitivity
0.25 cyc/deg
0.5 cyc/deg
1 cyc/deg
2 cyc/deg
4 cyc/deg
Background Spatial Frequency

2003-2004


Contrast Sensitivity Function For Third Graders
Students Who Played 10 Times
ER-Initial CSF
ER-Maximum CSF
IR-Initial CSF
IR-Maximum CSF
10000
1000
100
10
Contrast Sensitivity
0.25 cyc/deg
0.5 cyc/deg
1 cyc/deg
2 cyc/deg
4 cyc/deg
Background Spatial Frequency
p < 0.00008

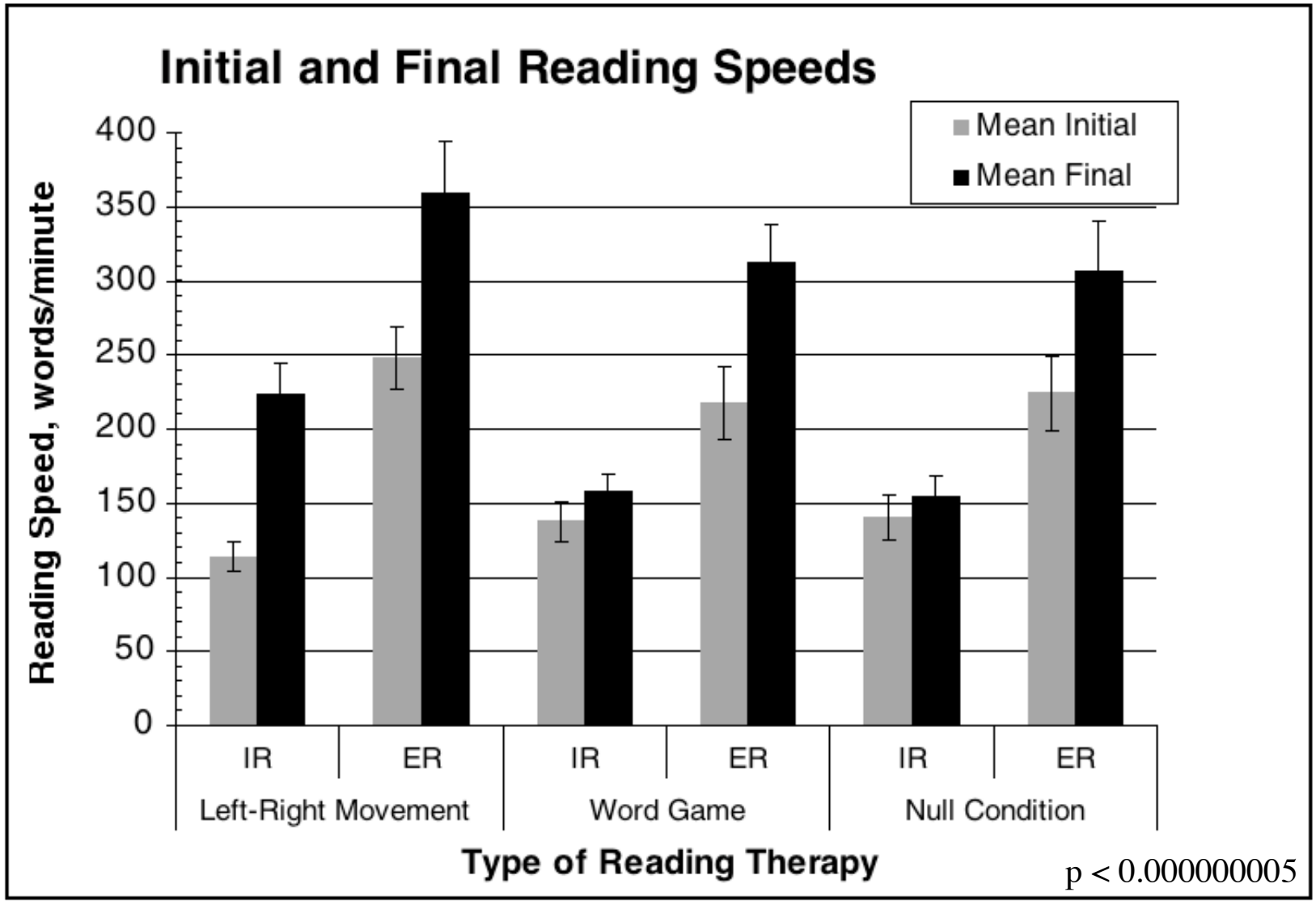
2003-2004

Reading Fluency Results in NIH Study

- Following 15 weeks of practice (30 times), reading speed doubled for **inefficient readers** who practiced direction discrimination (treatment).

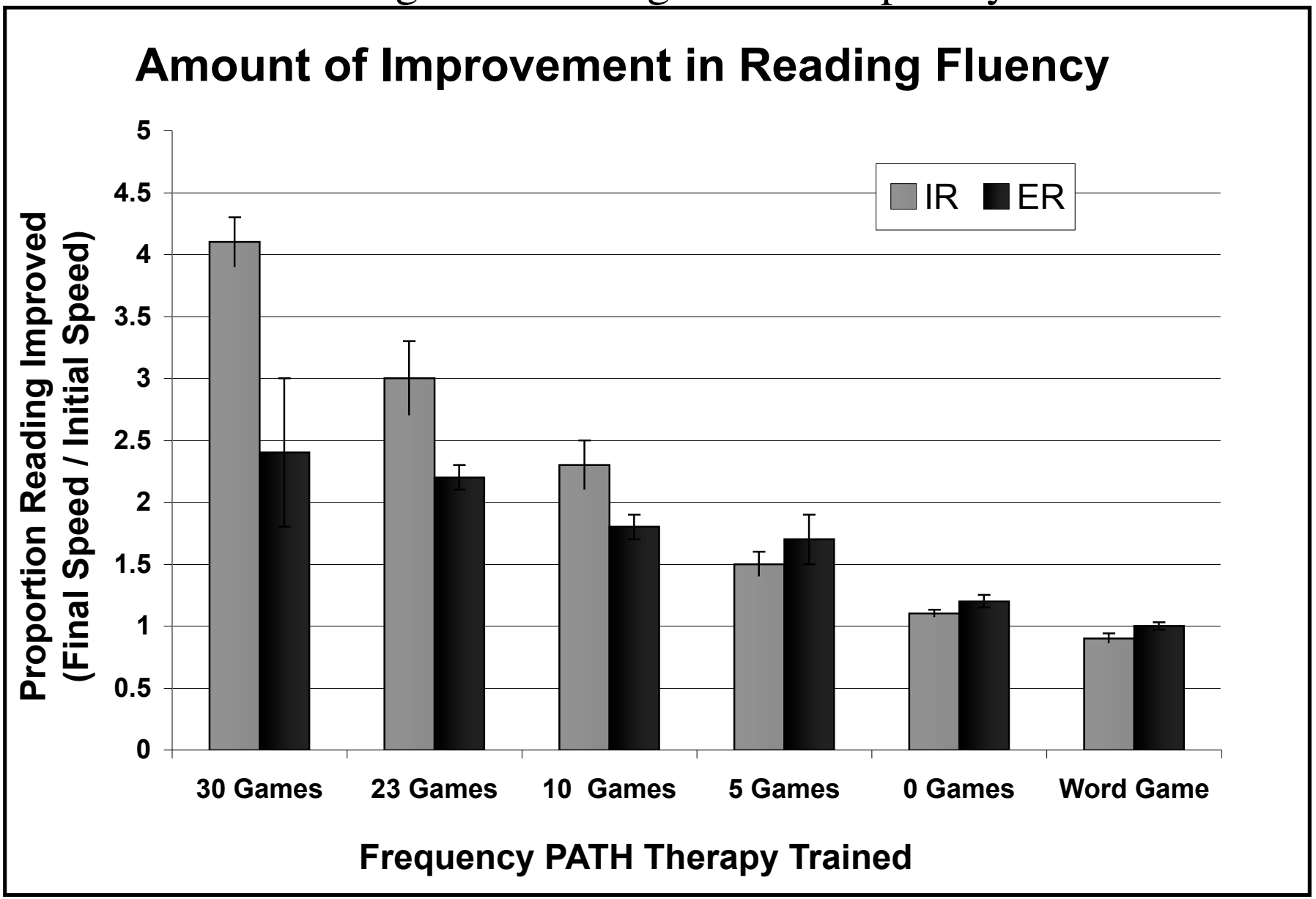
- Children who practiced word discrimination or no computer game (controls), however, showed little or no improvement overall in reading speed.

- This difference in the amount of improvement in reading speed between treatment and control groups was highly significant, $p < 0.000000005$].

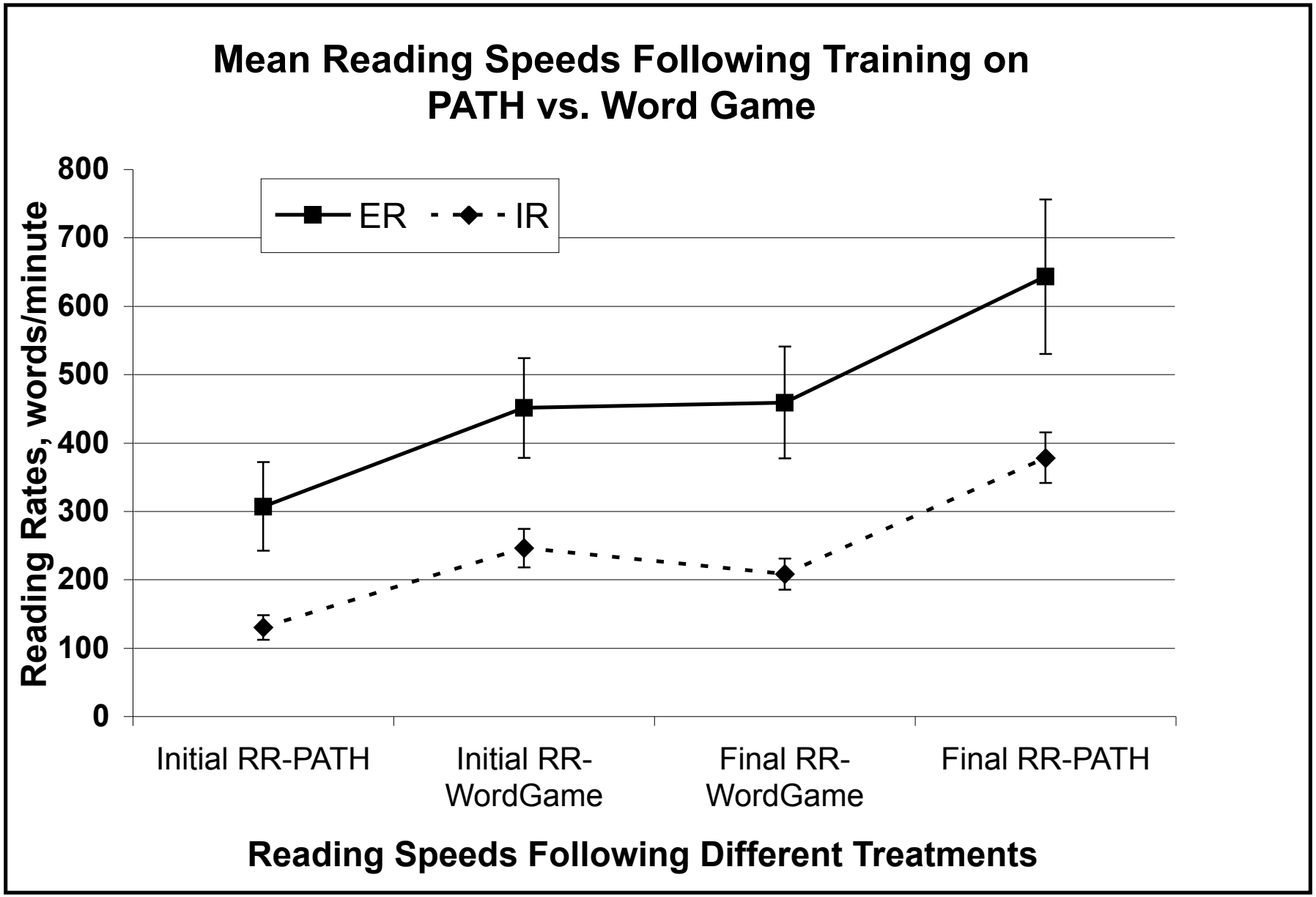


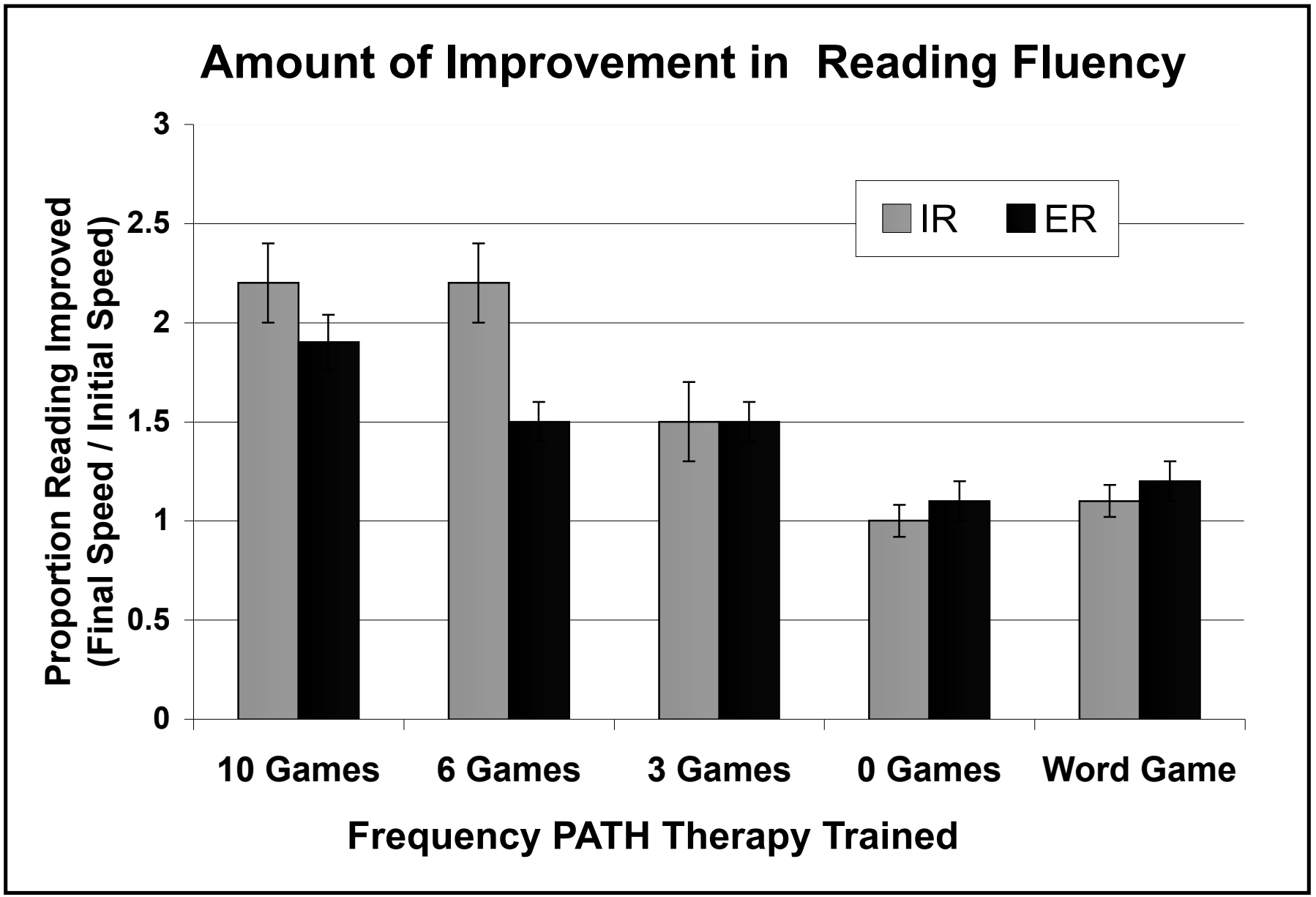
NIH Study: 2002-2003

PATH Training When Background Complexity Increased

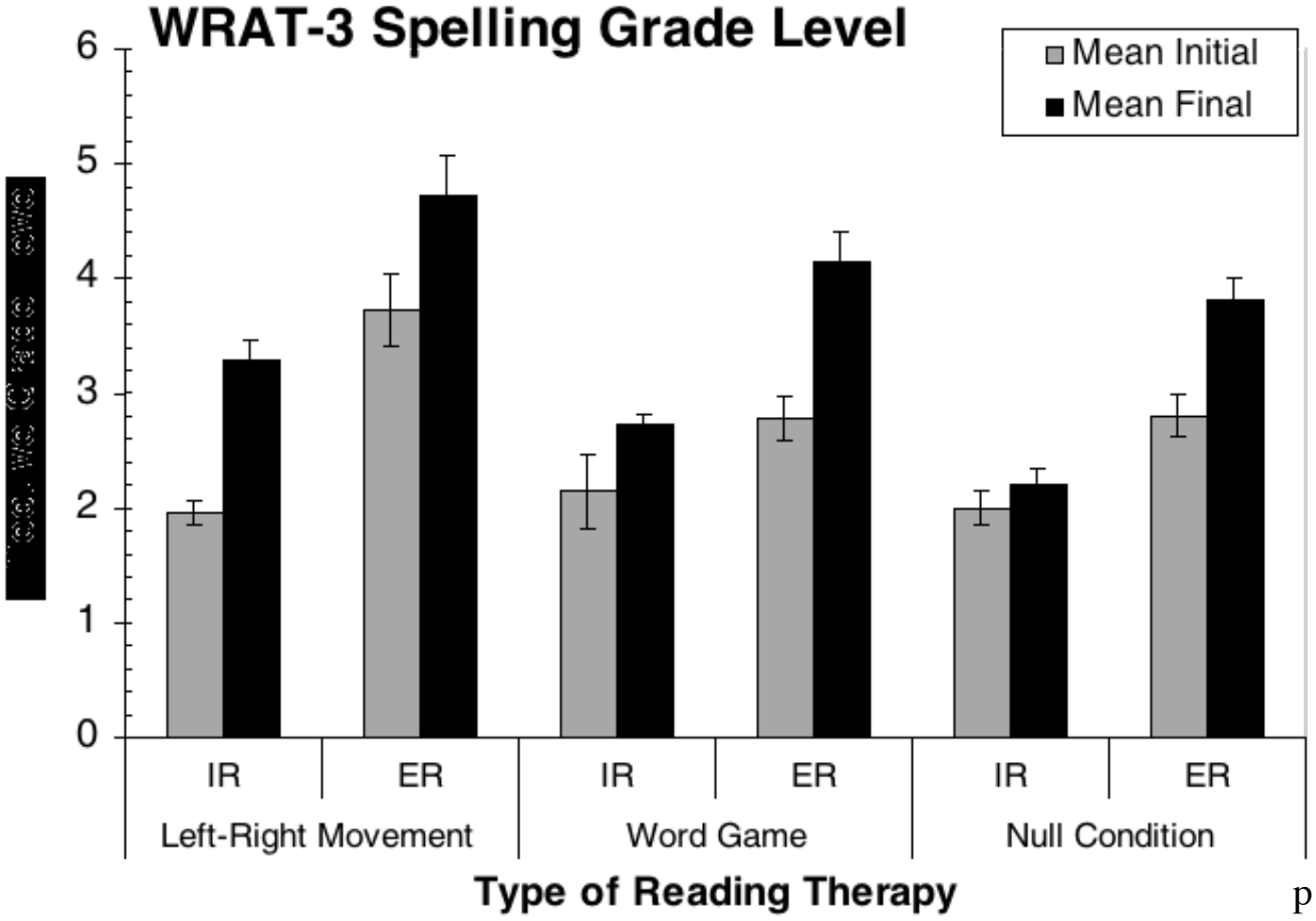


2003-2004


Mean Reading Speeds Following Training on PATH vs. Word Game
Reading Rates, words/minute
800
700
600
500
400
300
200
100
0
ER
IR
Initial RR-PATH
Initial RR-WordGame
Final RR-WordGame
Final RR-PATH
Reading Speeds Following Different Treatments

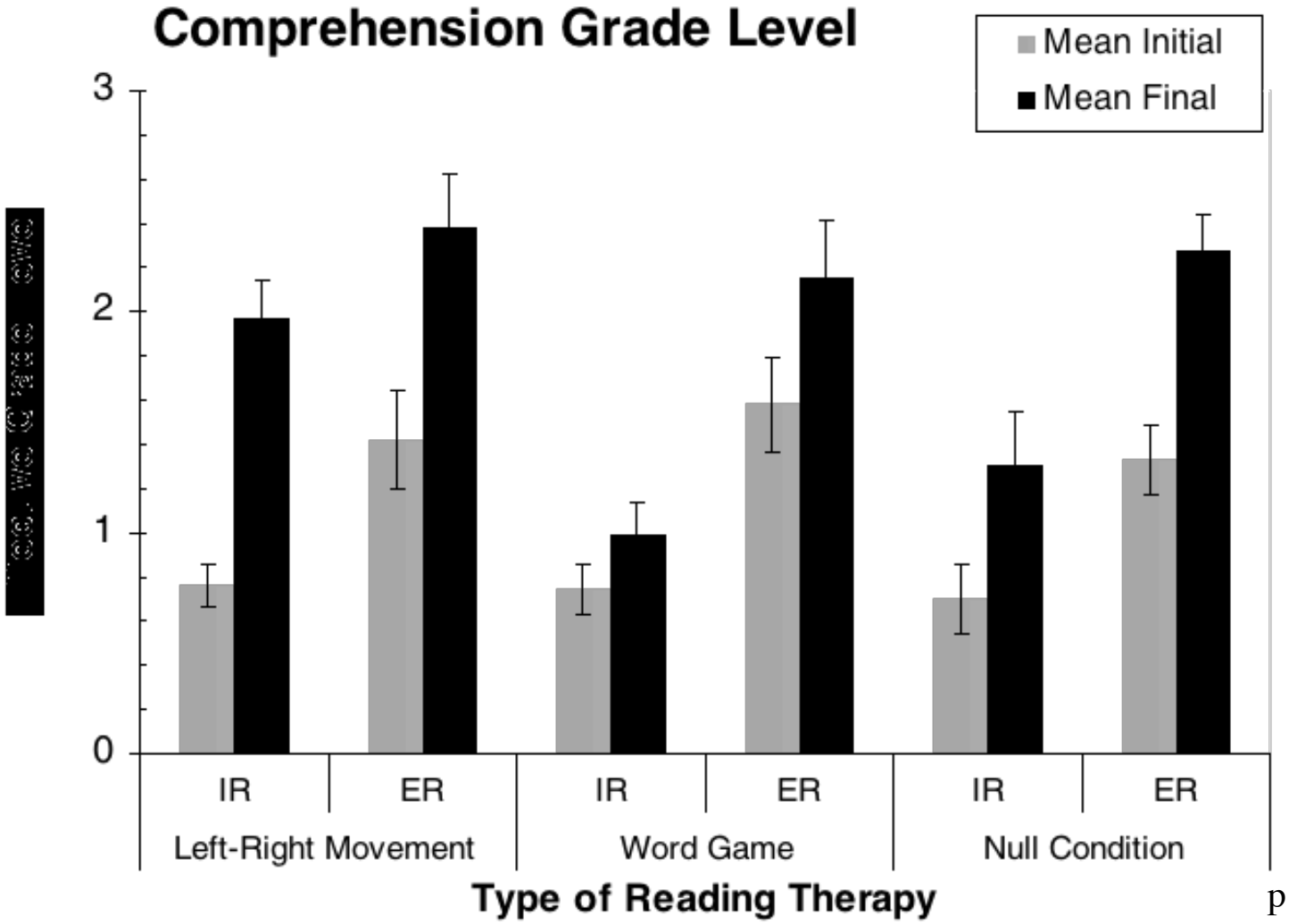

Amount of Improvement in Reading Fluency
Proportion Reading Improved
(Final Speed / Initial Speed)
3
2.5
2
1.5
1
0.5
0
IR
ER
10 Games
6 Games
3 Games
0 Games
Word Game
Frequency PATH Therapy Trained

2003-2004



$p < 0.0007$

NIH Study



$p < 0.005$

NIH Study

Direction Discrimination Linked to Reading Ability

- The greater the reading deficit, the more reading skills improved.
- Training on left-right movement discrimination improved reading skills from 1 to 3 grade levels.
- Reading speeds increased 2 to 4 fold following training on left-right movement discrimination:

  1) as number of training sessions increased, and
  2) as pattern complexity increased.

Table 1. Average Grade Level (GL) and range of improvement on each of the reading skills tests for inefficient readers who practiced direction discrimination, word discrimination and the null condition, in that order, in study funded by NICHD at NIH.

Reading Skills Test	Initial GL	Final GL	Minimum GL Improvement	Maximum GL Improvement	Mean GL Improvement
DDT Reading GL	2.9	4.3	0	**2**	**1.3 ± 0.3**
	3.3	3.4	-2	1	0.1 ± 0.4
	2.9	2.9	-2	1	0.0 ± 0.4
WRAT-3 Reading GL	2.7	3.9	0	**2.7**	**1.1 ± 0.2**
	2.7	3.5	0.3	1.2	0.7 ± 0.1
	2.9	2.9	-0.8	0.5	0.1 ± 0.2
WRAT-3 Spelling GL	2.1	3.3	0	**1.9**	**1.2 ± 0.2**
	2.1	2.7	-0.9	1.4	0.6 ± 0.3
	1.8	2.2	0	0.7	0.4 ± 0.1
Comprehension GL	0.8	2.1	0.1	**2.9**	**1.2 ± 0.2**
	0.7	1.0	-0.4	0.9	0.2 ± 0.2
	0.8	1.4	-0.2	1.5	0.5 ± 0.2

Summary of Improvements in Reading Skills

- The PATH therapy is the first to show significant **improvements in** children's **direction selectivity** and **reading performance** following 10 minutes once or twice a week of **training contrast sensitivity for direction-selectivity** using a fun computer game-like intervention for all types of inefficient readers.
- Previous investigations have shown that rarely does perceptual learning generalize to a new task.
- This study, in contrast, demonstrates that training on direction discrimination leads to:

  1) **a 2-4 fold increase** in reading fluency, and

  2) significant improvements in reading efficiency:

     1-3 grade levels on a wide range of literacy skills.

Direction Discrimination and **Not Flicker** is the Correct Dependent Variable for Diagnosing and Remediating Dyslexia

- Only when direction discrimination is measured do all dyslexics show lower sensitivity to movement discrimination

- Only when direction discrimination is measured **relative to** a textured background (motion contrast thresholds), and not a uniform field, do all types of dyslexics have a lower sensitivity to movement discrimination

Perceptual Learning / Cortical Plasticity

- Training direction discrimination network improves reading using the **inverse of principal of univariance**: once two stimuli are able to be differentiated by the visual system, this information can be used at subsequently higher levels of processing for discrimination, such as in the language areas.

- This mechanism would enable training at low levels in the visual system to produce significant improvements in reading, especially if reading deficits are caused by immature direction discrimination neural networks.

Immature Motion Pathways Account For Reading Deficits

- Immature motion-sensitive cells:
  1) would not signal brain in advance of the pattern-sensitive cells.
  2) might be causing a deficit in attention by preventing the pattern-sensitive cells from isolating the relevant information.
  3) would explain temporal and spatial sequencing deficits, and slow reading rates

- Therefore, the frame of reference would not be demarcated so that the position of: 1) the letters in the word, and
  2) the word in the text could be read easily.

Improved Reading Skills Following PATH Therapy

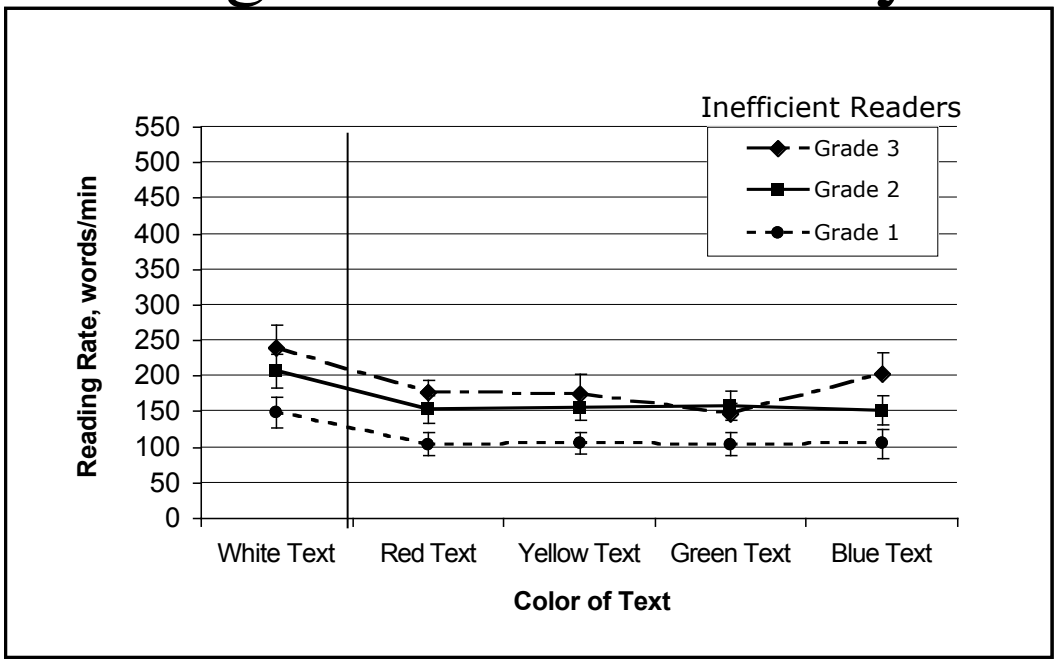
- Reading gets easier
- Reading out loud and silently is noticeably faster
- Comprehension improves
- Stories are reread less often to understand it
- Individual words stand out more easily
- Letters are more easily distinguished
- Spelling is easier
- Writing to summarize a story is easier
- Reading is less tiring
- Reading assignments take less time
- Following a sequence of instructions is easier

Characteristics of ‘PATH to Reading’ Therapy

[Effective and efficient training techniques based on neurobiology]

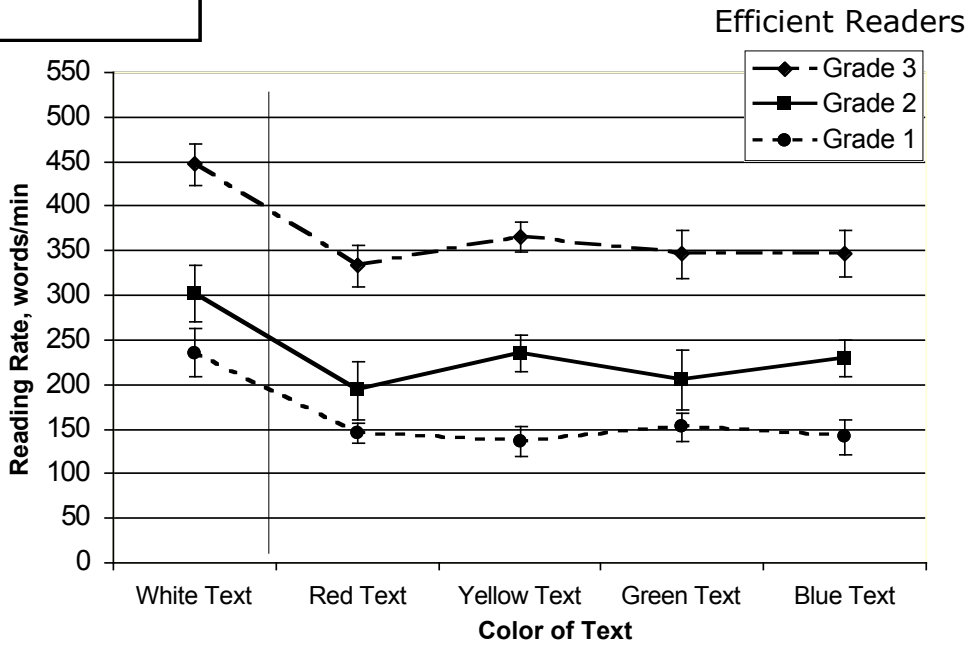
- Remediates rather than compensates
- Not language nor reading level specific
- Allows for the inefficient reader to be trained in the least restrictive environment
- Synergistic with all educational approaches
- The more severe the reading problem, the greater the rate of improvement
- Provides noticeable improvements in reading ability, student’s desire to read, self-esteem, resulting in long-term effects on learning
- First time any study has found a training method that improves the reading deficits of both phonological origin (requires accurate temporal sequencing) and orthographical origin (requires accurate spatial sequencing).

Magnocellular Pathways Control Reading Fluency



Colored Text Read 30% More Slowly

Colored Text Read 30% More Slowly



Colored Text That Is Filtered To Compensate For CSF Losses Also Read 30% More Slowly

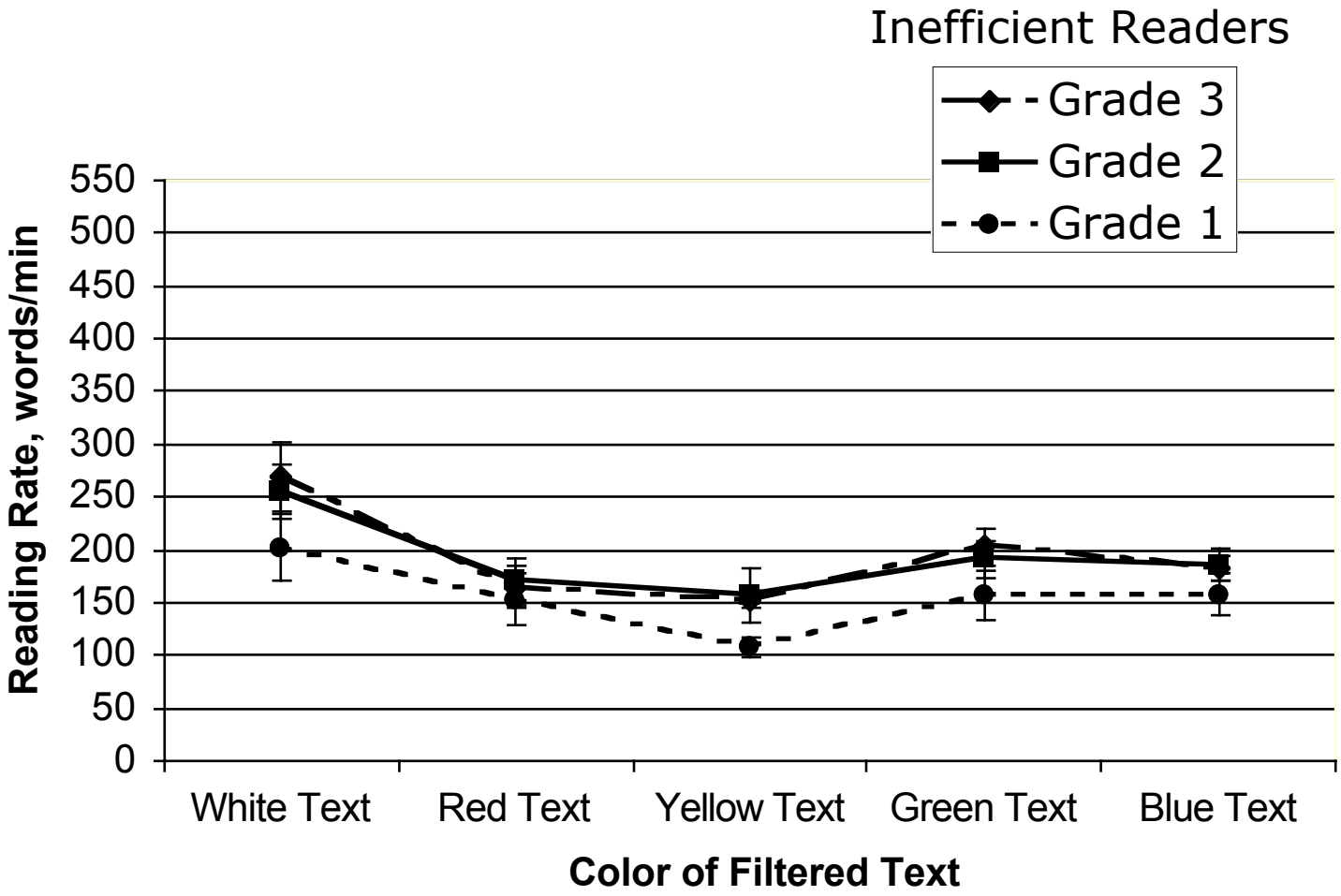


Image Enhancement Improves Reading Performance

- Orientation discrimination Contrast Sensitivity Functions (CSFs) were used to determine individualized image enhancement filters.
- The individualized filters, causing white text on a black background to be displayed in shades of gray, are matched to each observer's CSF, to compensate for their CSF losses, when compared to a normal adult reader.
- Precompensation filtering for a known degradation (characterized by CSF losses) is used to improve reading performance (both magnification and reading rate thresholds).

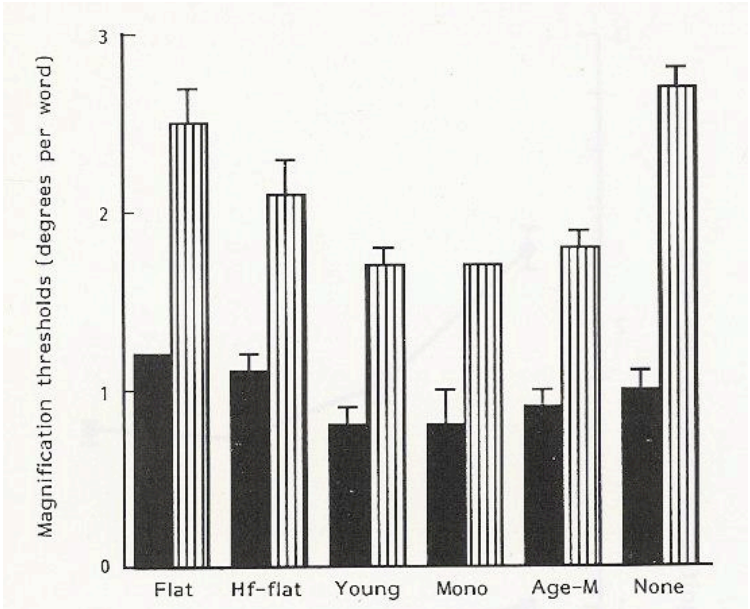


Figure 5 Magnification thresholds for ARM observers using different image enhancement filters: ■, atrophic ARM; ▥, disciform ARM

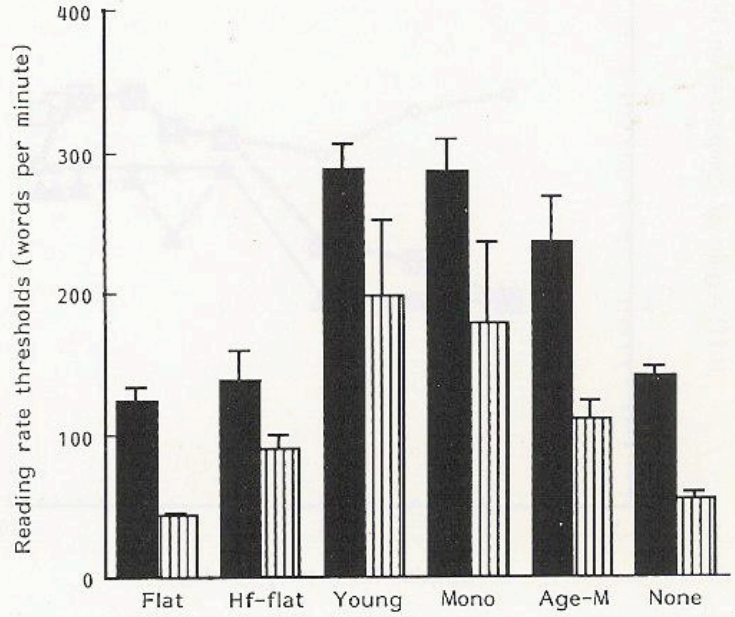


Figure 6 Reading rate thresholds for ARM observers using different image enhancement filters: ■, atrophic ARM; ▥, disciform ARM

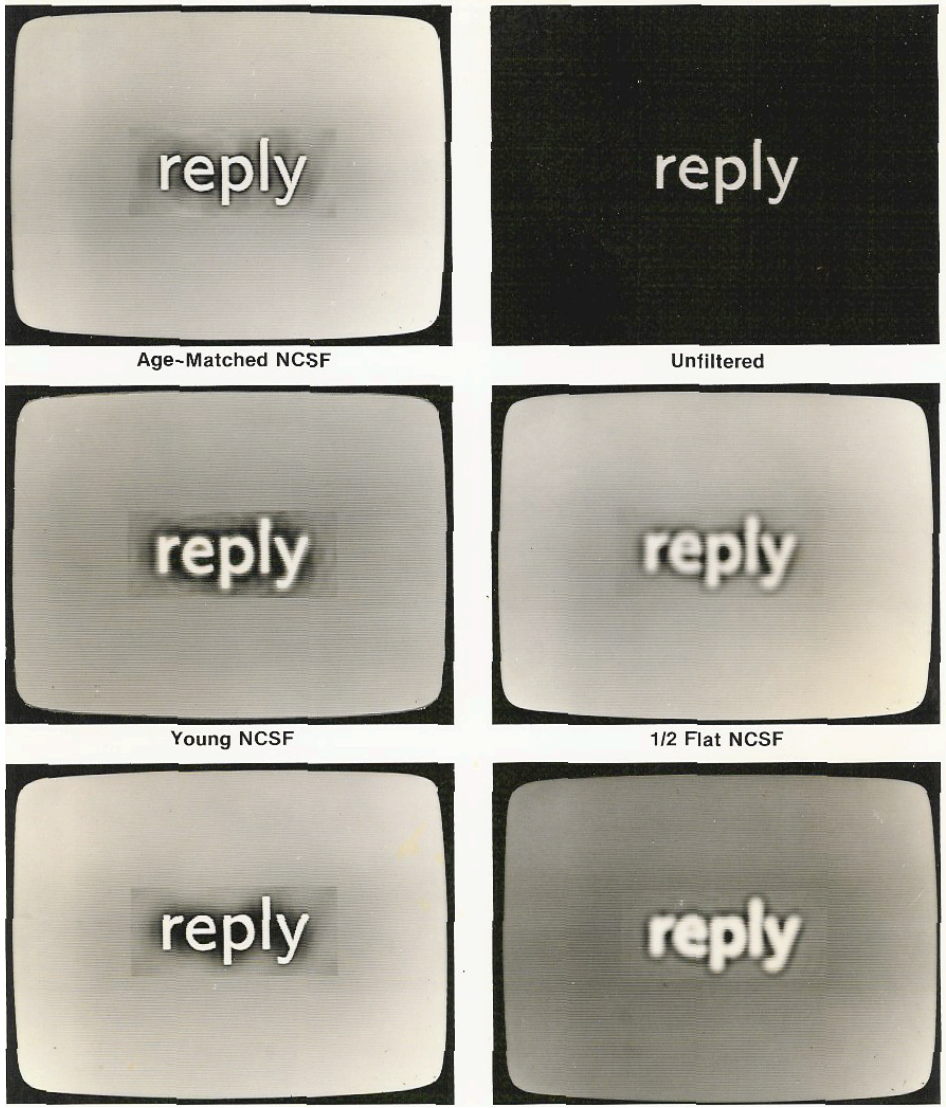


Image Enhancement Algorithms

- The transfer function chosen for the image enhancement filter is:

  $H(f) = NCSF(f) / [(NCSF^2(f) + (1/2MaxGain)^2)]$

  where f is the radial spatial frequency expressed in cyc/deg by: $f = sqrt(u^2 + v^2)$, u and v are the horizontal and vertical spatial frequency, respectively, and

  NCSF(f) = Child's or Low Vision CSF(f) / Adult's CSF(f)

- The maximum amount of enhancement in the spatial frequency domain is set by the factor MaxGain. MaxGain was discovered empirically to be dependent on the display's pixel density, such that a higher MaxGain, *i.e.* more enhancement, is needed when the screen has a lower pixel density.

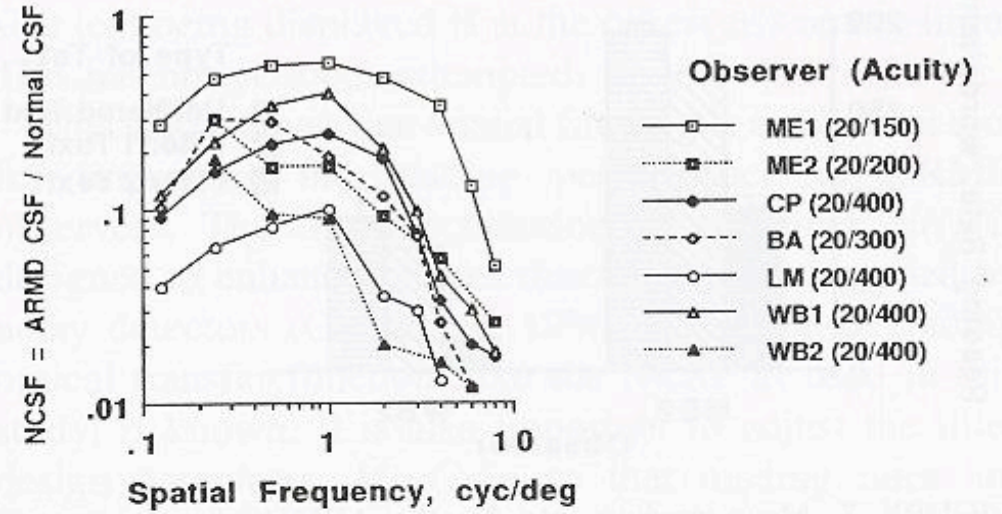


FIGURE 5. Normalized contrast sensitivity functions *(NCSF)* of ARMD observers.

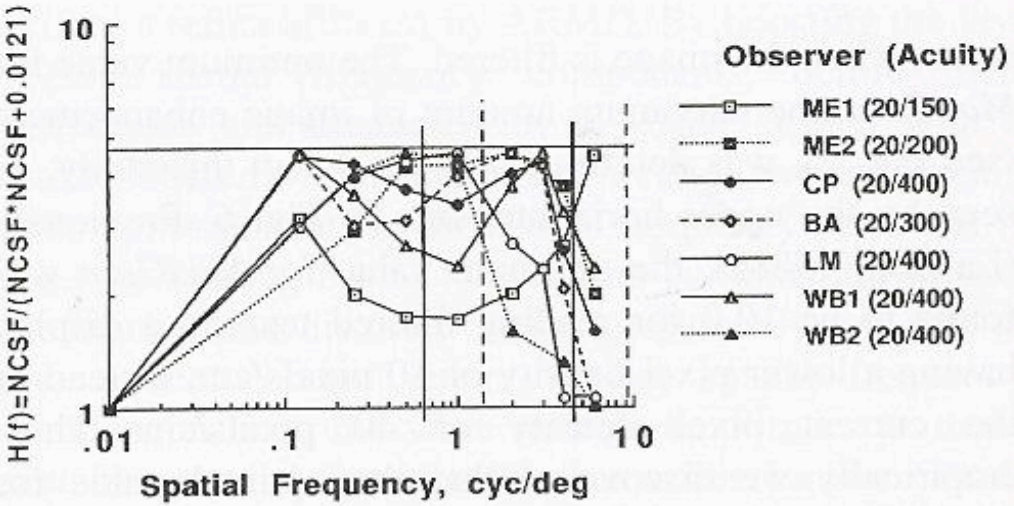
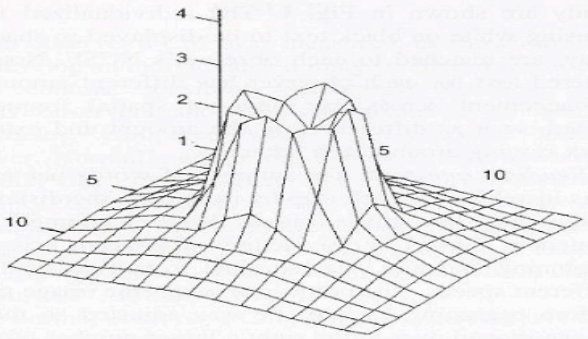
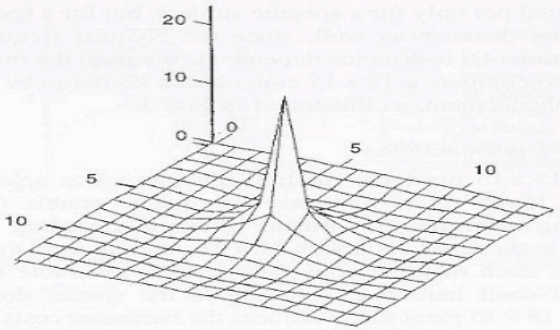


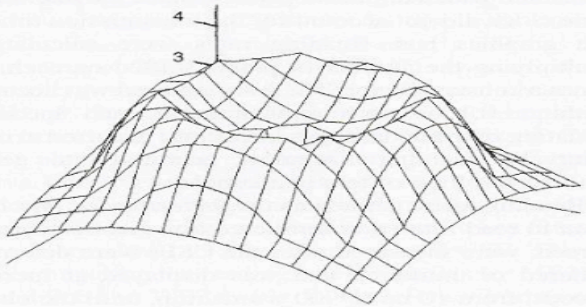
FIGURE 6. The image enhancement transfer function *H(f)* for ARMD observers.



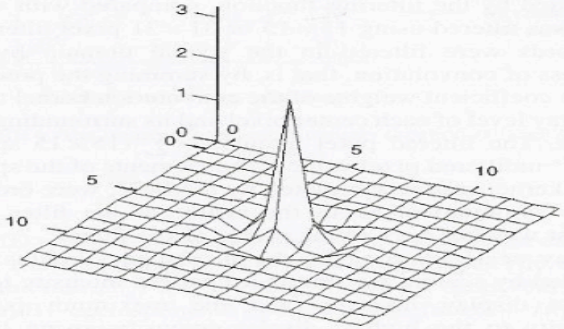
Filter 1 Transfer Function



Filter 1 Convolution Kernel



Filter 2 Transfer Function



Filter 2 Convolution Kernel

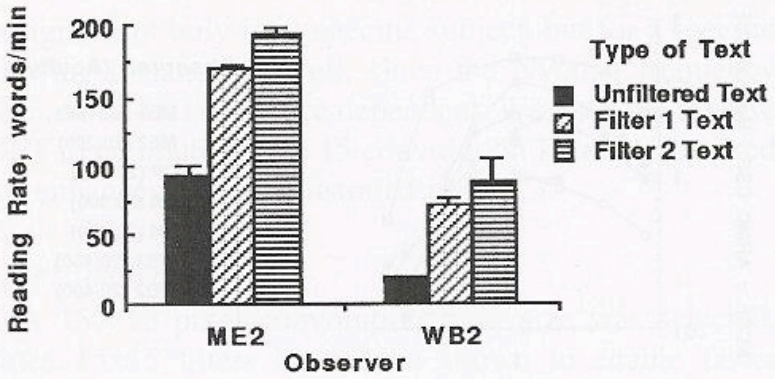


FIGURE 7. Mean reading rate for the ARMD observer to read unfiltered and two types of filtered (Filter1 and Filter2) text.

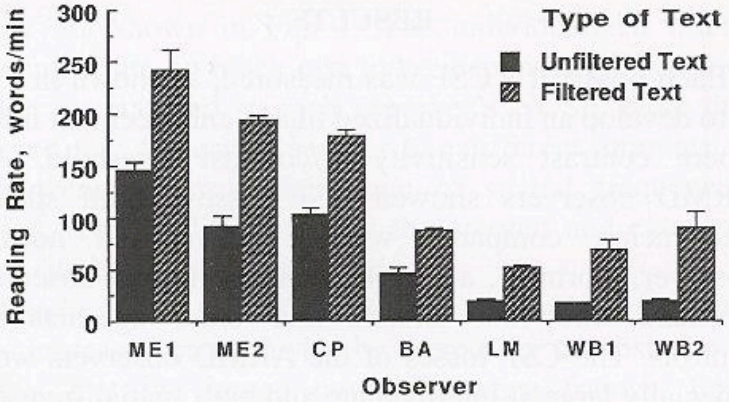
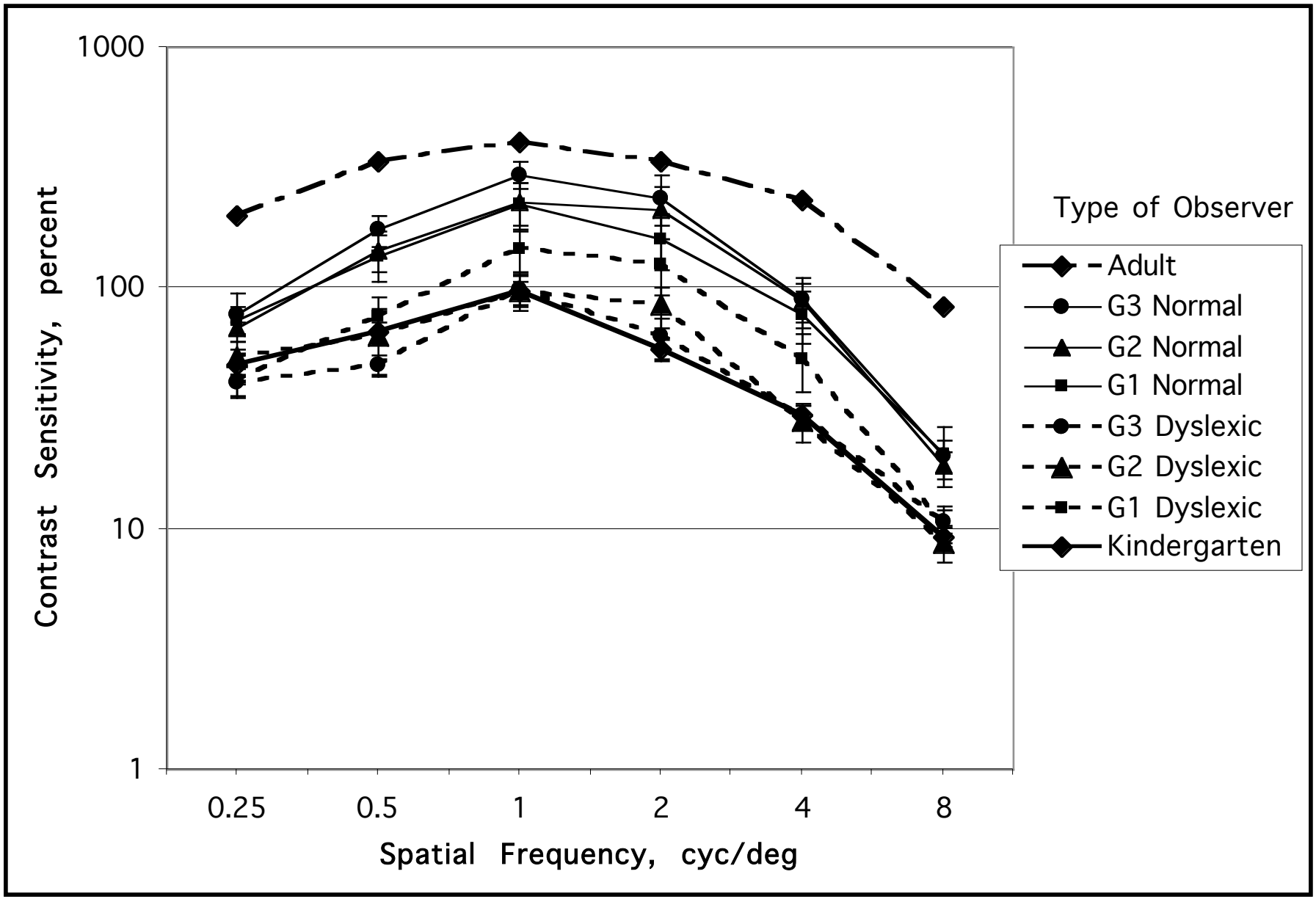


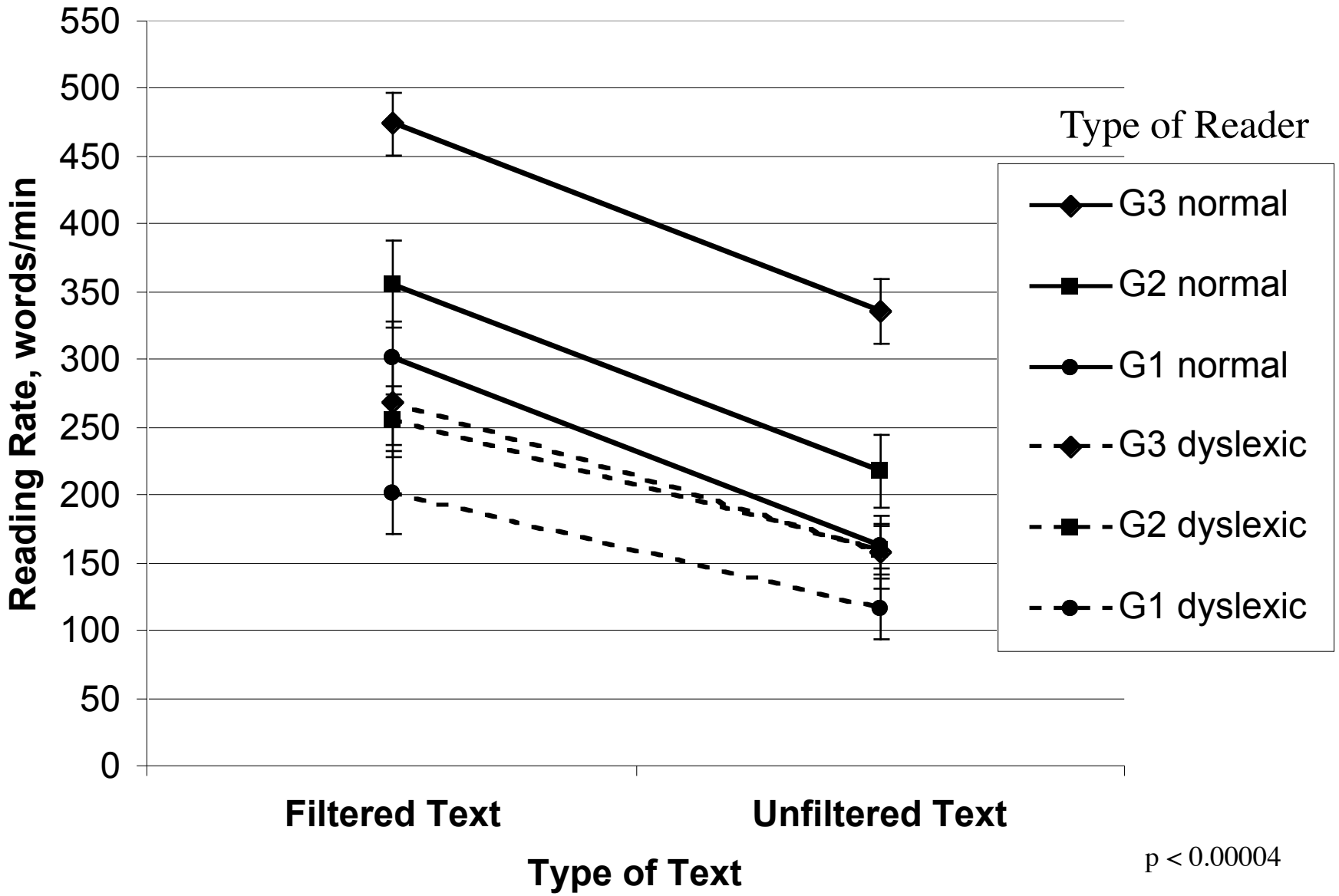
FIGURE 8. Mean reading rate for the ARMD observer to read unfiltered and filtered (Filter2) text.

Filtered Words for Different Children

Orientation Discrimination CSFs

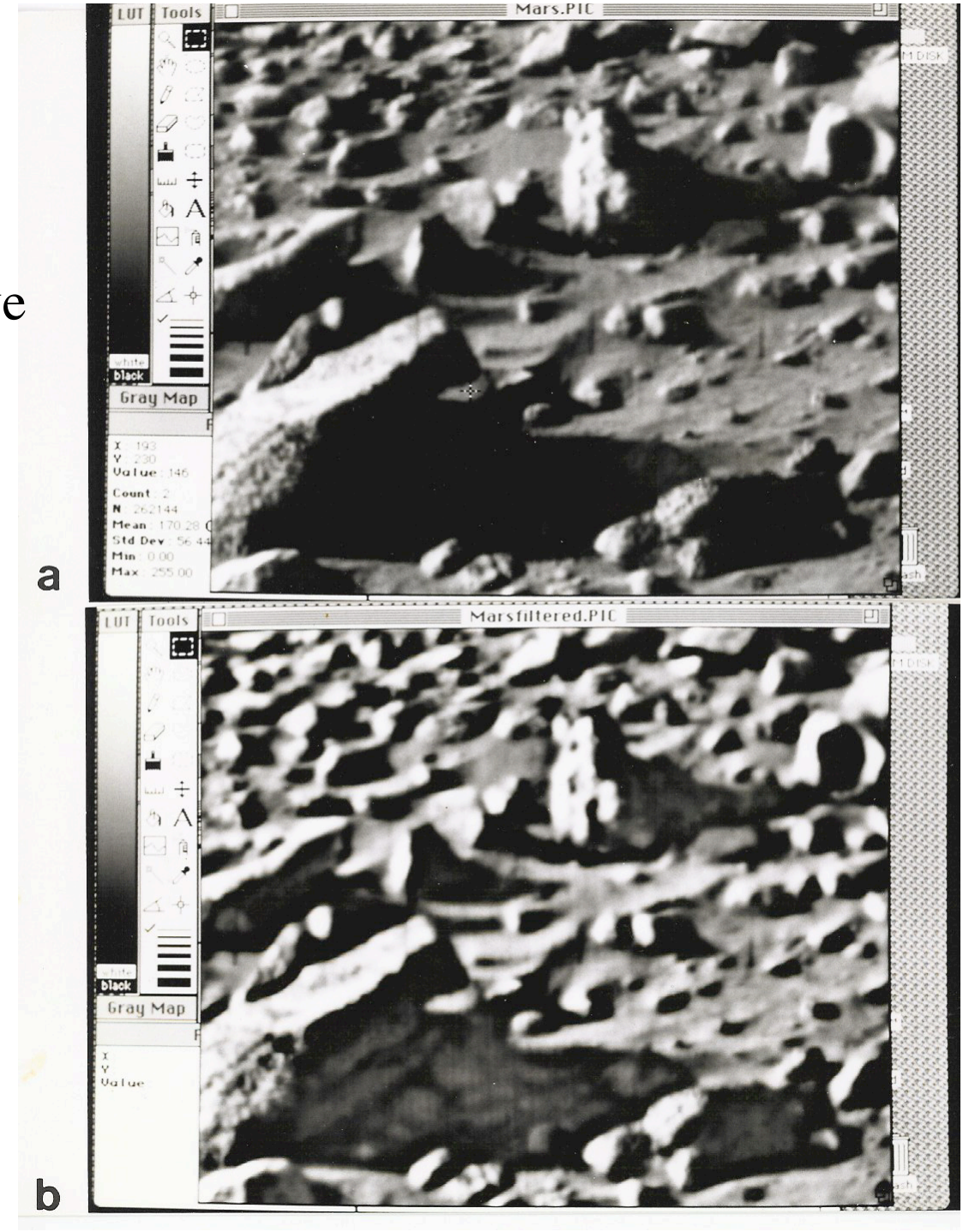


Reading Rates for Filtered and Unfiltered Text For Children



$p < 0.00004$

Image Enhancement Algorithms also improve ability of automated computational vision systems to navigate by uncovering objects hidden under shadows



Dynamic Object-Based 3-D Scene Analysis Using Multiple Cues

- Developed Computational Visual System (CVS) that segments objects in natural scenes using algorithms and filtering elements discovered by studies in neuroscience.
- This CVS classifies different types of patterns, based on object shape, texture, position in visual field, amount of motion parallax in subsequent scenes without any *a priori* models.
- This object-based representation focused on object formation found in dorsal cortical pathway used to locate objects in scene.
- Algorithms that incorporate 1) the relative weighting of different object attributes used for object discrimination and 2) dynamic time warping were used to instantiate computational networks that incorporate both competitive and cooperative networks.

Comparison of Approaches for Computational Vision Systems

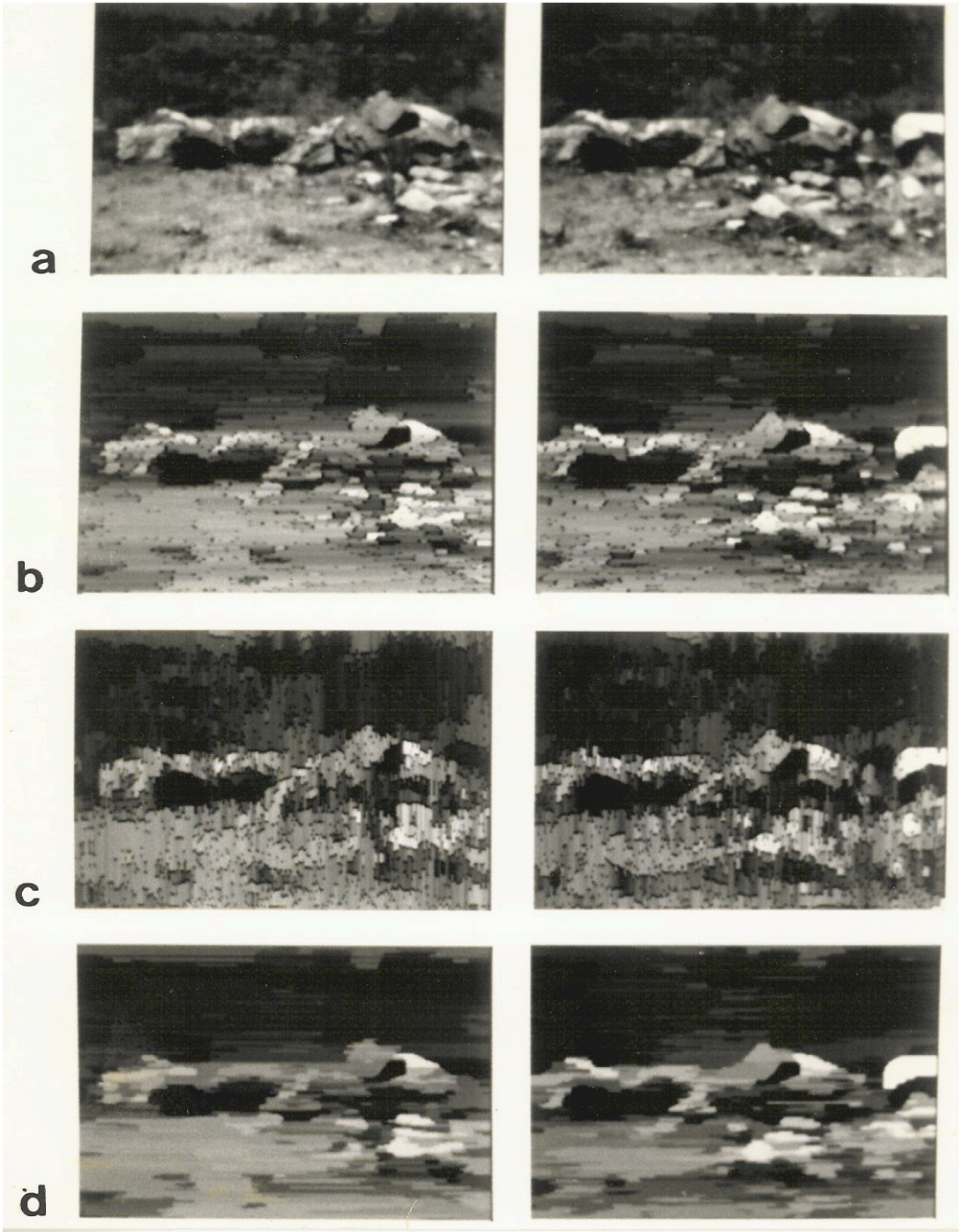
Type of Processing	Old Way	New Way
Scene Representation	Pixel-Based	Object-Based
Filters	Circulary-Symmetric	Oriented Even- and Odd-Symmetric
Object Matching	Cross-Correlation	Gradient, Dynamic Time Warping, Competitive & Cooperative Networks
Computations	Serial	Parallel and Serial
Sensory Modality	Preattentive Vision Using Intrinsic Scene Properties	Both Preattentive and Attentive Vision Using Sensory Fusion that is Based on Biological Processes
Depth Extraction	Static Stereo	Dynamic Motion Parallax, Multiple Object Atrributes (Effects of Shadows, Scene Noise, and Occlusion Reduced)
Feedback	Limited, Not Dependent on Sensory Fusion	Controls Dynamic Working Range and Adaptive Thresholds (Based on Psychophysics)
Scanning	Exhaustive	Event-Based Subsampling Within Variable Windows of Attention
Learning	None, Supervised, or Bayesian	Unsupervised Event-Based Using Multiple Object Attributes

a. Two views of natural scenes that were compensated for contrast, pitch, heading, roll (dynamic time warping), so only translational movement used.

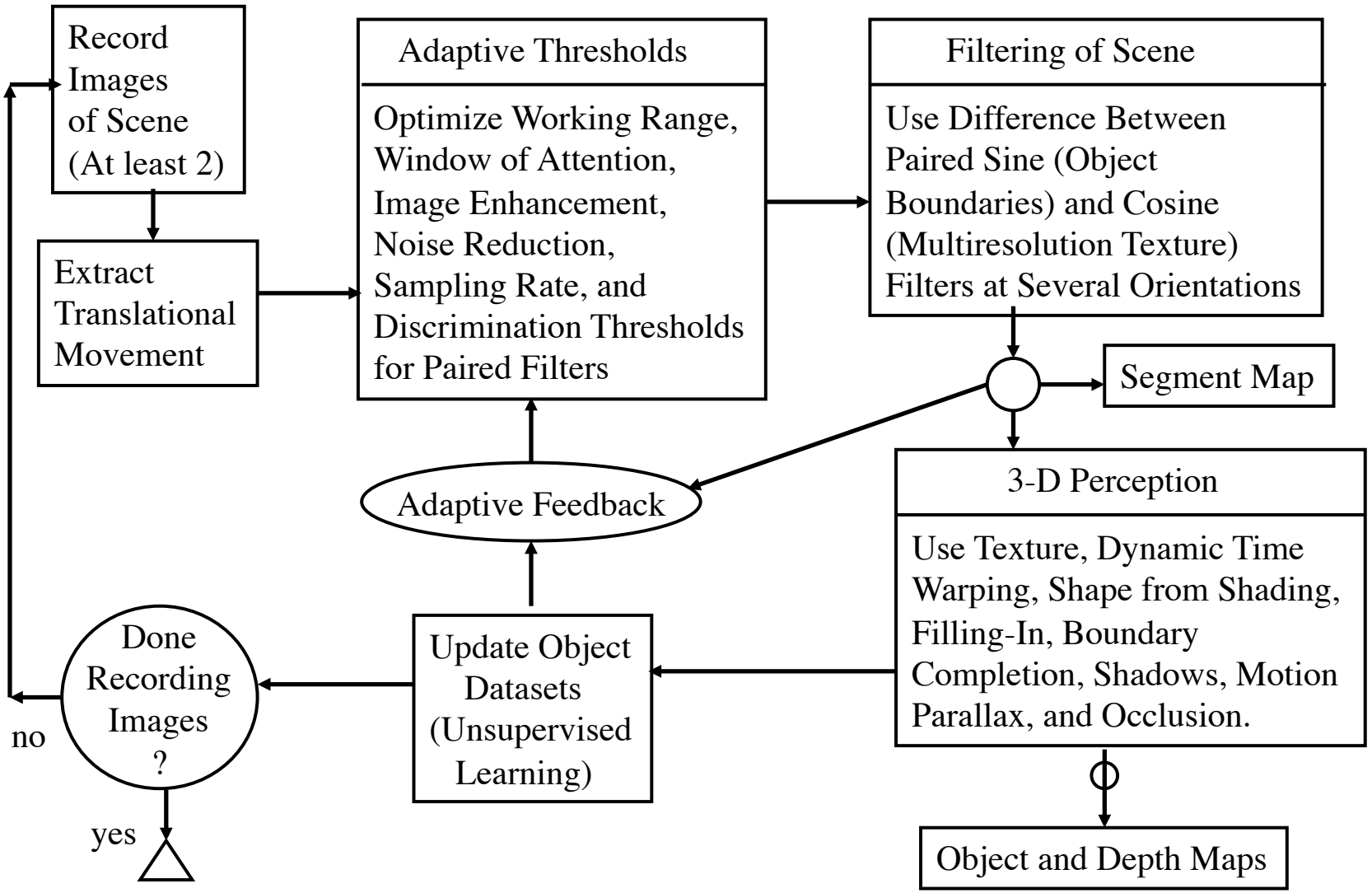
b. Horizontal Segment Maps by paired odd- and even-symmetric filters, using multiattribute approach with both noise reduction and global optimization

c. Vertical Segment Maps

d. Object Maps constructed from combining Horizontal and Vertical Segment Maps



Current CVS: Construct 3-D Object Map

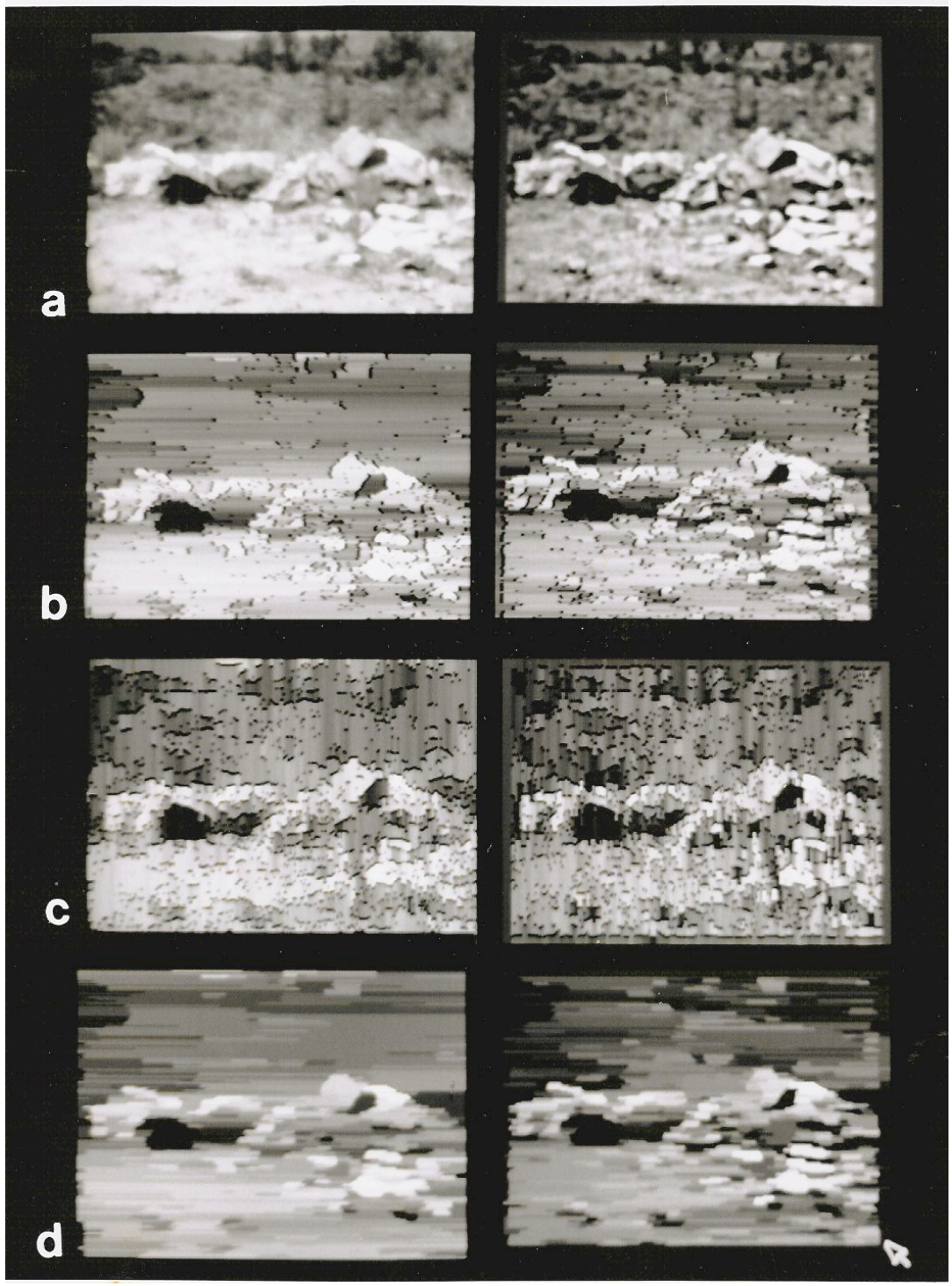


a. Unenhanced (left) and Enhanced (right) views of same natural scene.

b. Horizontal Segment Maps

c. Vertical Segment Maps

d. Object Maps constructed from combining Horizontal and Vertical Segment Maps

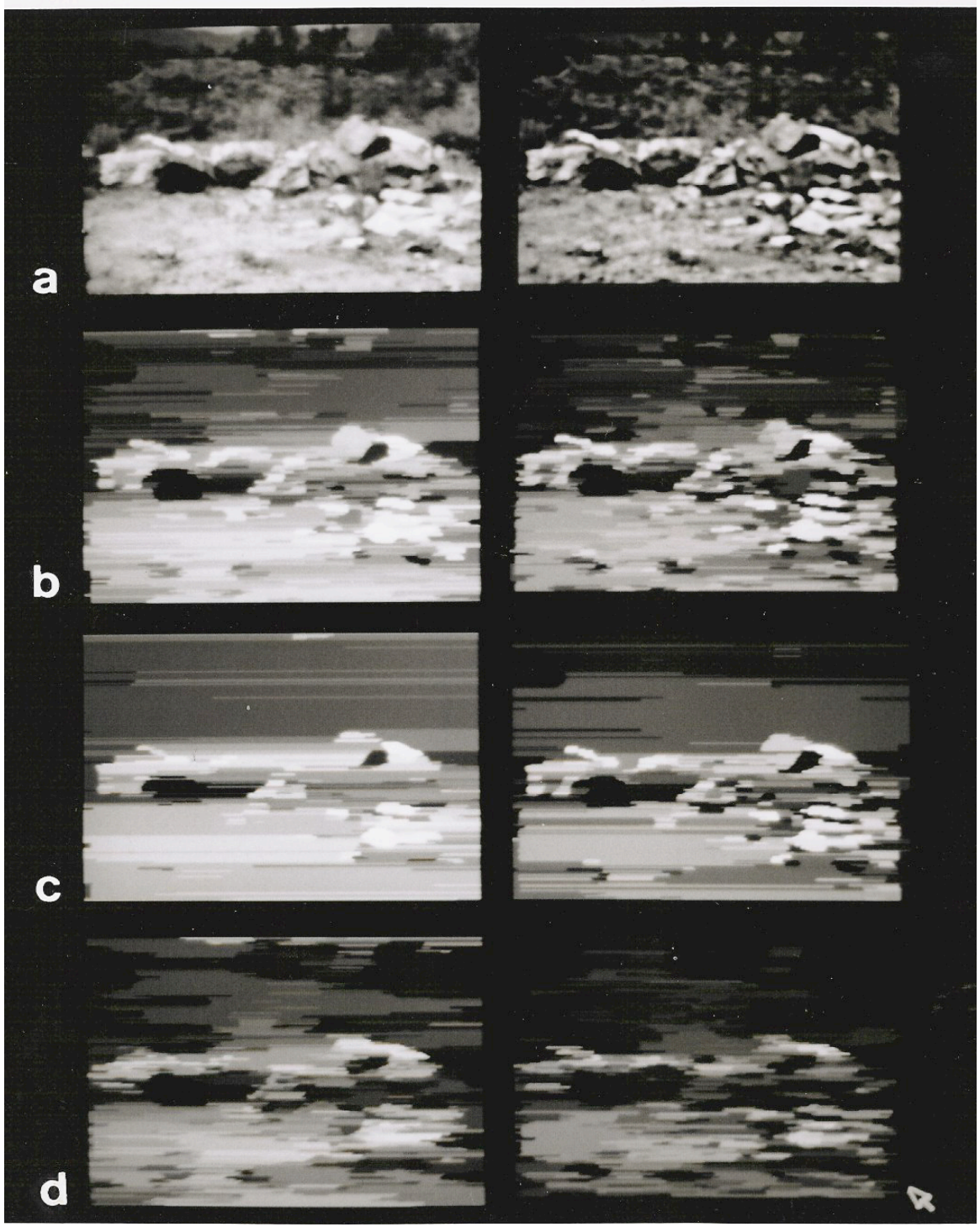


a. Unenhanced (left) and Enhanced (right) views of same natural scene.

b. Best boundary detection parameters:
Filter size = 7 pixels long, minsize=4 pixels
Sine amplitude= 5 Gray Levels (GL) for horizontal maps, 3 GL: vertical maps

c. Best boundary detection parameters:
Filter size =7 pixels long, **Except now**
Sine amplitude= 10 GL: horizontal maps,
6 GL: vertical maps

d. Best boundary detection parameters:
Sine amplitude= 5 GL: horizontal maps,
3 GL: vertical maps
Except now Filter size = 13 pixels long



Algorithms For Image Enhancement and Automated Computational Vision Systems

- Improves object segmentation to aid Reading, Learning, and Navigation.

- Multiattribute approach using both global and local filtering, competitive and cooperative networks, based on cognitive neuroscience of dorsal pathway, enables developing more robust and adaptive learning systems for navigation in natural scenes.

- CVS using dynamic, layered neural networks with feedback enables testing effectiveness of models of cortical architectures using adaptive, event-based learning systems to aid robots and people with reduced vision to navigate through unknown terrain.

Summary of Improvements in Reading Skills Following Training of Dorsal Pathway

- Previous investigations have shown that rarely does perceptual learning generalize to a new task.
- Our research, in contrast, demonstrates that practicing direction discrimination relative to backgrounds increasing in complexity leads to:

  1) **a 2-4 fold increase** in reading fluency, and

  2) significant improvements in reading efficiency

  (**1-3 grade levels** on a wide range of literacy skills).
- The MTR therapy is the first to show significant **improvements in** children's **reading performance** following 7.5 minutes once or twice a week of **training contrast sensitivity for direction-selectivity** using a fun computer game-like intervention.