

Visual Learning and the Brain: Implications for Dyslexia

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ABSTRACT—The central and peripheral visual fields are structurally segregated in the brain and are differentiated by their anatomical and functional characteristics. While the central field appears well suited for tasks such as visual search, the periphery is optimized for rapid processing over broad regions. People vary in their abilities to make use of information in the center versus the periphery, and we propose that this bias leads to a trade-off between abilities for sequential search versus contemporaneous comparisons. The parameter of periphery-to-center ratio (PCR) describes the degree of peripheral bias, which evidence suggests is high in many people with dyslexia. That is, many dyslexics favor the peripheral visual field over the center, which results in not only search deficits but also (more surprisingly) talents for visual comparison. The PCR framework offers a coherent explanation for these seemingly contradictory observations of both deficit and talent in visual processing. The framework has potential implications for instructional support in visually intensive domains such as science and mathematics.

VISUAL LEARNING AND THE BRAIN: IMPLICATIONS FOR DYSLEXIA

One of the most remarkable findings about the neurology of primate vision is that the brain largely preserves the retinotopic map of the visual field, so that any given region in the vis-

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ual cortex projects back to a unique portion of the visual field (Daniel & Whitteridge, 1961). A consequence of this correspondence is that information from the central and peripheral parts of the visual field are largely segregated in the brain, and because (as we will discuss) these visual fields differ in both their functional and anatomical properties, these regions may be reasonably thought of as distinct (Levy, Hasson, Harel, & Malach, 2004). Building on the axiom of a center-periphery distinction, we argue that people's relative abilities to use information in the center versus the periphery strongly affect their relative abilities for visual search and comparison.

We define a useful parameter called periphery-to-center ratio (PCR) that describes the degree to which a person favors one region over the other. We also discuss converging evidence, which suggests that at least some subset of people with dyslexia may be biased to favor information in the periphery over the center (i.e., they constitute a high-PCR group) and illustrate how this can account for observed deficits for tasks such as visual search, but more surprisingly, for talents in spatial learning and the perception of visual anomalies. The PCR framework allows us to predict, with some degree of precision, how individuals differ in their abilities to learn from specific presentations of visual information, which, if corroborated, may have important implications for teaching and learning.

TWO VISUAL SYSTEMS

The human visual system is organized concentrically around a point in the fovea of the retina. This simple fact about the geometry of the retina is surprisingly powerful in predicting how people respond to visuospatial stimuli in their environment. The central region of the visual system can resolve fine detail, but only for a tiny portion of the visual field at any one time. The surrounding periphery, on the other hand, is on average an order of magnitude less acute but stands watch

over an angular field that is roughly three orders of magnitude larger in area (see Figure 1). And though the information in the periphery is coarsely sampled, it is sufficiently rich to allow people to discern, say, whether an object is an animal or a rock, even at the peripheral extremes (Thorpe, Gegenfurtner, Fabre-Thorpe, & Bulthoff, 2001).

The center and the periphery are optimized for very different needs. For example, while the center appears more sensitive to faces, the periphery is better at perceiving buildings and scenes (Levy et al., 2004). And while the center is helpful when searching for small objects (Carrasco, Evert, Chang, & Katz, 1995), the periphery is better for rapid discriminations (Carrasco, Giordano, & McElree, 2006). Functional differences like these can be traced to differences in the anatomy of the visual system that, from retina to cortex, serve to distinguish the visual response characteristics of these regions.

For example, in the retinal center, the distribution of cone cells peaks sharply, while rods are absent, forming an annulus around this central point that peaks about -20° off center (Curcio & Allen, 1990). The ganglia that pool and process the outputs of the photoreceptors also differ in the center and periphery. While 90% of the ganglia in the center are classified as (parvocellular) midget cells, these cells represent only about half the ganglia found in the periphery, where larger (magnocellular) parasol cells tend to dominate (Dacey, 1994). Such physiological differences in the retina are carried over to the brainstem and visual cortex in such a way as to largely preserve the retinotopic organization of the eye. As a result, the center and the periphery are grossly segregated throughout the brain (Gattass et al., 2005) and can be considered for many intents and purposes as separate yet complementary visual systems.



Fig. 1. Two visual systems are contrasted in a fish-eye photograph of Harvard Yard covering 180° in visual extent. We invite the reader to hold an arm outstretched and compare this figure with their own perceptions. For reference, a thumb held at arm's length subtends a visual angle of approximately 2° (O'Shea, 1991). The inset scales normally sized text to the visual angle spanned by the hand. (The centermost 2° of this field contains the fovea, a region marked by the greatest concentration of cone cells but an absence of rods.) Now, while maintaining fixation on the back of the hand, we invite the reader to defocus attention so as to become aware of the wealth of detail evident outside the -16° peripheral region spanned by the hand. In contrast to the central regions used in reading, the angular area visible in the periphery is immense, and much detail can be discerned even in the far periphery. We assert that people differ in their relative abilities for making use of information in the small central field versus the broad peripheral field, and the extent to which one is favored over the other can determine a person's relative proclivities for focused search tasks versus broad comparisons.

Though the center and periphery are functionally and anatomically different, it is impractical to define a clear anatomical boundary separating these regions. Changes in the distribution of cones occur sharply -1.5° from the center, but gross changes in the distribution of ganglia occur more gradually, becoming pronounced -10° out. Experiments examining the top-down effects of cognitive load on vision show qualitative differences in response characteristics beginning at -8° (Plainis, Murray, & Chauhan, 2001; Schwartz et al., 2005). Though it may be difficult to precisely demarcate a center-periphery boundary, for the purposes of this discussion, we take this to be at -8° , where changes in attentional response become pronounced.

What If ... the Center and Periphery Were in Fact Independent?

In astronomy, it is common to use a coarse instrument, with a broad field of view, to search for large-scale structures across the sky, or to monitor for sudden changes occurring in random locations, without warning (e.g., the onset of a supernova). More costly telescopes, capable of high resolution over a narrowly restricted field of view, are used to study details in objects only after interesting locations are pinpointed using the wide-field instrument. Making an analogy to astronomical telescopes, let us take as a working hypothesis that the center and the periphery of the human visual system can indeed be considered independent instruments or systems. Doing so, we see that many fundamental differences in visuospatial response, including some pertaining to memory and attention, can be understood simply as a consequence of the differences in visual area covered by each of these regions. For example, the only way the central system can compare features that are widely separated in visual angle (i.e., by more than the diameter of the region) is if the eye is moved so that broadly separated features are scanned sequentially by its narrow field. Because the scanning is sequential, it necessarily takes place over time, and working memory is needed to process broad comparisons made via this region (Inamdar & Pomplun, 2003). In fact, experiments show that when a gaze-contingent window is used to isolate the center from the periphery, the load on available working memory increases (Osaka & Osaka, 2002). By the same token, if comparative judgments are made using the peripheral system, demands on working memory are reduced because even widely separated features can be perceived almost simultaneously in this broad field of view. And indeed, the peripheral field appears to be optimized for making such contemporaneous comparisons, as evidenced by the fact that the speed at which visual dis-

criminations are made increases significantly with increasing eccentricity (Carrasco, McElree, Denisova, & Giordano, 2003; Carrasco et al., 2006).

The load on attentional processing is similarly affected by the preferential use of one region over the other. The center's restricted field of view reduces attentional demands because it is narrow and, in effect, acts like blinders on a horse to limit the number of distracters that need to be processed at any given time. The periphery, on the other hand, receives information from many locations at once and is therefore prone to confusion, limiting the region's utility in the presence of distracters or noise. Experiments show that, when searching for objects in a field of distracters, visual search is more efficient when the central parts of the visual field are used (Carrasco et al., 1995; Cornelissen, Bruin, & Kooijman, 2005). Thus, when conceptualized as separate systems, use of the center versus the periphery introduces a trade-off between attention and working memory, which in turn affects the utility of each region when performing comparisons that are sequential (such as visual search) versus comparisons made more contemporaneously across broad extents. These differences are summarized in Table 1.

Assuming that people—for whatever reasons—vary in their abilities to make use of information presented in the center versus the periphery, we can define a conceptual parameter called the PCR that reflects the variation in this bias.¹ A bias favoring the center or the periphery could occur because of factors that are temporary or permanent, due to causes that are physical, physiological, or neurological in origin. For example, task design can temporarily affect PCR, say, through use of scotopic lighting that favors the periphery, thereby raising PCR. In contrast, cognitive load in the center can reduce performance in the periphery (e.g., Williams,

Table 1
Visuospatial Properties of Center Versus Periphery

<i>Property</i>	<i>Center</i>	<i>Periphery</i>
Perceived field of view	Narrow	Broad ($\sim 1:10^3$)
Confusion from distracters or noise	Low	High
Need for attention in spatial comparisons	Low	High
Processing speed	Slow	Fast
Need for working memory in spatial comparisons	High	Low
Concurrent spatial processing	Poor	Good
Sequential visual processing (e.g., visual search)	Good	Poor
PCR characteristics	Low PCR	High PCR

Note. PCR = periphery-to-center ratio.

1982) and would temporarily lower PCR. Physiological changes associated with aging (Ball, Beard, Roenker, Miller, & Griggs, 1988), injury to the parietal regions of the brain (Posner, Walker, Friedrich, & Rafal, 1984), or drugs such as vigabatrin (Kalviainen et al., 1999) reduce peripheral ability and should lower PCR. Damage to the retina from diseases such as glaucoma or macular degeneration would also bias a person's PCR. Thus, under our rather broad definition, any factor that biases a person's ability to use information in the periphery over information in the center would increase PCR, and vice versa, biasing abilities for concurrent and sequential processing (as well as demands for working memory and attention) as summarized in Table 1.

Attention Segregates PCR Groups

Whether physical, neurological, or task-dependent factors are primarily responsible for the initial bias toward the center or the periphery, top-down attentional processes likely amplify this bias so as to further segregate PCR groups. For example, when attention is paid to a task in the central field, while simultaneously observing the periphery, functional magnetic resonance imaging results show that neural activity corresponding to the peripheral region is suppressed in the visual cortex (Schwartz et al., 2005). This constriction of the peripheral field under high attentional load in the center has been known for some time (Leibowitz & Appelle, 1969) and is a phenomenon familiar to airplane pilots (Williams, 1995).

There is evidence to suggest that a reciprocal effect takes place in the periphery, such that task load in the periphery suppresses perception in the center (Plainis et al., 2001). Here, the threshold for detecting a simple light, presented peripherally over a range of eccentricities from 5° to 30°, was measured while a cognitive task (e.g., discrimination of numerical digits) was simultaneously carried out in the central field. As expected, task load in the center suppressed the ability to perceive the peripheral light. But, surprisingly, performance in the center was found to reciprocally affect the simple detection task in the periphery, suggesting that the center and the periphery interfere under attentional task load.

If an individual has a bias that tends to statistically overstimulate the center over the periphery, such a bias will on average increase the attentional load in the center, which in turn will further suppress the periphery (Schwartz et al., 2005). Similarly, a bias that statistically overstimulates the periphery will tend to suppress the center (Plainis et al., 2001). Thus, reciprocal inhibitory interactions between the center and the periphery, due to mechanisms of attention, will statistically subdivide high- and low-PCR groups. Rather than a

continuum of abilities that range from central to peripheral, we would expect abilities associated with high- and low-PCR groups to be relatively bimodal, segregating populations with abilities for sequential/central visuospatial processing from those with proclivities for comparative/peripheral tasks.

DYSLEXIA: A HIGH-PCR GROUP?

Developmental dyslexia, a disorder that affects abilities for reading and writing, is one of the most prevalent learning disabilities diagnosed among school-aged children in the United States (Shaywitz & Shaywitz, 2005). Though the specific etiology of dyslexia is unresolved (Ramus, 2004), it is generally accepted that at least some subset of this population exhibits wide-ranging impairments in low-level visual processing (for a review, see Vellutino, Fletcher, Snowling, & Scanlon, 2004). Visual deficits in the perception of luminance contrast, coherent motion, flicker, persistence, and other processes associated with the magnocellular system are often linked with dyslexia (e.g., Eden, VanMeter, Rumsey, & Zeffiro, 1996; Livingstone & Hubel, 1988). In this section, we consider the possibility that people with dyslexia may constitute a high-PCR group (biased toward the periphery) and use the PCR framework to interpret recent findings pertaining to visuospatial abilities in dyslexia.

Before proceeding with this discussion, a caveat is in order. We wish to emphasize that dyslexia is a heterogeneous disorder, likely consisting of several meaningful subtypes (e.g., Morris et al., 1998). Given the complex and multifaceted nature of reading failure (e.g., Fischer, Rose, & Rose, 2007), it is unlikely that any single factor alone (including the peripheral bias discussed here) can account for all of the rich variability inherent in the dyslexic phenotype. Although most of the visual research we draw upon to build our argument did not differentiate between subtypes of dyslexia (for exceptions, see Lorusso et al., 2004; Slaghuis & Ryan, 2006), it is important to point out that we expect the relevance of the PCR model to be limited to a subset of the dyslexic population. For purposes of this article, we will conceptualize the link between peripheral processing abilities and dyslexia in the broadest possible terms, keeping in mind that future research will be needed to more precisely characterize this relationship.

Impetus for the PCR Approach

The development of the PCR framework was motivated by an attempt to reconcile seemingly contradictory findings about

whether dyslexia is associated with compensating talents in visuospatial domains (cf., Winner et al., 2001). Ever since “word blindness” was first described as a specific disability nearly a century ago, researchers speculated that individuals with dyslexia may possess talents in certain visuospatial domains (Orton, 1925), which would account for their success in visually intensive pursuits, such as science or art (Everatt, Steffert, & Smythe, 1999; Fink, 2006; Wolff & Lundberg, 2002). From the extant visual literature on dyslexia, it is apparent that characteristics rightly described as deficits in the context of reading can be perceived as talents when reexamined from other standpoints. For example, peripheral distractibility, observed to be a detriment in reading (Geiger & Lettvin, 1987; Rayner, Murphy, Henderson, & Pollatsek, 1989), could be perceived as a talent if the task at hand involved the detection of visual anomalies in the periphery. However, because the peripheral field is less important than the central field in reading (Rayner & Bertera, 1979), it is perhaps not surprising that few investigators have systematically probed these sorts of visual differences in dyslexia. Therefore, the insights raised by the PCR framework may have escaped notice in the literature on dyslexia simply because of the focus on reading and the neglect of other visual skills, despite the fact that the pertinent neurological findings supporting this model (described below) have been known for decades.

Evidence of Peripheral Bias Associated with Dyslexia

Evidence that some individuals with dyslexia exhibit a visual bias toward the periphery first came to light in studies measuring letter identification in the peripheral field (Geiger & Lettvin, 1987; Geiger, Lettvin, & Zegarra-Moran, 1992). In these studies, researchers used a mechanical shutter (tachistoscope) to briefly flash (for -10–25 ms) pairs of letters simultaneously in the center and in the periphery, observing accuracy of response as a function of eccentricity for the outermost letter. These researchers found that dyslexics tended to perform slightly worse than normal readers when the outside letter was presented in the central field (within -5°), but they performed better than controls when the outermost letter was presented in the periphery. Specifically, whereas normal readers could not identify letters above chance level at an eccentricity of -10° , dyslexics performed at above-chance levels as far out as -12.5° . In fact, one severely dyslexic man was able to recognize letters at -20° eccentricity. The seminal findings of Geiger and Lettvin were soon independently confirmed (Perry, Dember, Warm, & Sacks, 1989), and more recently reconfirmed in a large study involving 125 Italian

children (Lorusso et al., 2004). This latter work replicated Geiger and Lettvin’s original apparatus and furthermore divided the dyslexic children into Boder and Bakker subtypes. This work confirmed the earlier findings (Geiger & Lettvin, 1987; Geiger et al., 1992) and further showed that the enhanced peripheral effects appeared relatively insensitive to subtype.

Though Geiger and Lettvin’s findings were substantiated through a number of experiments, their work was heavily criticized early on, in part because the results appeared difficult to replicate using an apparatus such as a computer that lacked the temporal and spatial resolution of the tachistoscope (Geiger & Lettvin, 2000). For example, one study (Klein, Berry, Briand, D’Entremont, & Farmer, 1990) that used a relatively crude Apple II display found only marginal support for the effect Geiger and Lettvin claimed. Another study (Goolkasian & King, 1990) using the 12-inch monitor of a Macintosh II again offered only partial support. However, these partial nonreplications were sufficient to draw interest away from Geiger and Lettvin’s findings (Rayner, 1998), until other independent evidence (e.g., Facoetti, Paganoni, & Lorusso, 2000) sparked a resurgence in this work (Lorusso et al., 2004).

Despite the controversy, the letter recognition experiments were not the only evidence of peripheral bias in dyslexia. Grosser and Spafford (1989, 1990) used techniques of kinetic and static perimetry, common in ophthalmology, to map peripheral sensitivity to low-level color and intensity contrasts in dyslexics and controls. They found that, whereas average readers were able to identify colors to -10° – -20° eccentricity along the horizontal meridian, subjects they classified as severely dyslexic could identify colors as far out as -40° – -60° eccentricity. In addition, their studies observing peripheral sensitivity to the sudden onsets of randomly located low-level intensity contrasts also showed greater peripheral sensitivity in dyslexics (Grosser & Spafford, 1990). An independent variation on this latter experiment (Facoetti et al., 2000), which compared reaction times for the perception of randomly presented 20-ms flashes at 16 cardinal locations, again confirmed findings of enhanced peripheral response associated with dyslexia.

Stuart and Lovegrove (1992) proposed that Grosser and Spafford’s findings of enhanced peripheral sensitivity to colors and contrasts were consistent with anatomical, physiological, and behavioral evidence ascribed to abnormalities in postretinal transient (magnocellular) pathways associated with dyslexia. This evidence included postmortem histological studies that compared the brains of people with dyslexia and controls (Livingstone, Galaburda, Rosen, &

Drislane, 1991), revealing irregularities in the laminar structures of the magnocellular lateral geniculate nucleus in those with dyslexia. Other evidence included a substantial literature (described in Slaghuis & Ryan, 2006) citing behavioral and physiological evidence linking at least some subgroups of dyslexia with deficits for visual functions associated with these magnocellular pathways, including deficits for coherent motion detection, flicker fusion, and sensitivity to intensity contrasts. Regardless of the specific mechanisms, for purposes of the foregoing discussion, it is only important to note that there is a converging body of evidence suggesting that at least some people with dyslexia exhibit a visual bias favoring the periphery, characteristic of what we would call a high-PCR group.

Implications for Visuospatial Abilities in Dyslexia

If dyslexia constitutes a high-PCR group (biased to the periphery), then according to the arguments leading to Table 1, people with dyslexia in comparison to controls will show advantages for contemporaneous comparative operations as well as disadvantages for sequential visual discriminations. Consistent with this hypothesis, there is a body of research demonstrating both the disadvantages and the advantages: Dyslexics perform poorly on tasks involving visual search (e.g., Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Facoetti et al., 2000; Iles, Walsh, & Richardson, 2000), such as the visual serial reaction time task (Howard, Howard, Japikse, & Eden, 2006), which is a sequen-

tially presented search task that places extreme demands on visual working memory. They also perform two to three times worse on contour integration (Simmers & Bex, 2001), a visual search task (see Figure 2) that is easily confounded by peripheral confusion and thus especially difficult for high-PCR groups.

The research also documents the advantages for visual comparison in high-PCR groups, such as dyslexics, which show talents for tasks involving contemporaneous comparisons that are done better using the periphery. For example, the impossible figures task seems to be facilitated by a peripheral bias. In this task (see Figure 3), subjects must distinguish between possible figures and impossible ones, and make this discrimination as quickly as possible. In order to determine whether a figure is impossible, one portion of the figure must be compared against another, either visually or in memory, to note inconsistencies in the figure (see Figure 3c). Those more adept at making use of information in the periphery (high PCR) should be able to perform these comparisons quickly, with minimal need for working memory. However, those who tend to rely on information in the central visual field (low PCR) need to scan the figure sequentially, which requires that comparisons be made largely in working memory; thus, they should be less effective at this task. Interestingly, experiments show that people with dyslexia are, on average, able to discriminate both possible and impossible figures more rapidly than controls, without sacrificing accuracy for speed (von Karolyi, 2001; von Karolyi, Winner, Gray, & Sherman, 2003). These findings provide support for the notion that at least some individuals with

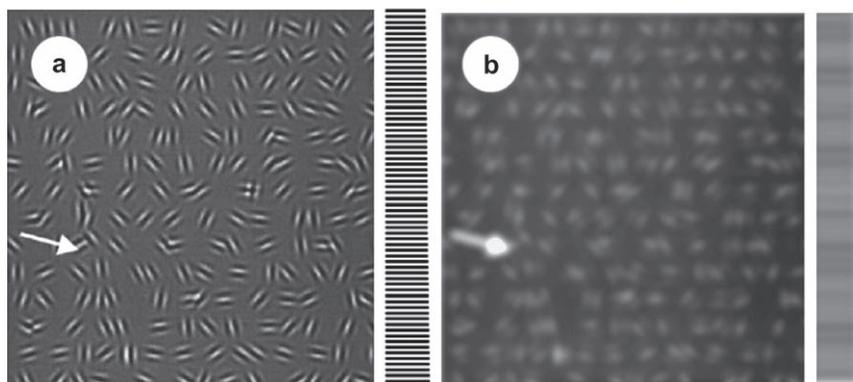


Fig. 2. Contour Integration Task. (a) Left: Those with dyslexia are 2–3 times less sensitive to the presence of a string of connected contour elements (arrow) compared to controls (adapted from Simmers & Bex, 2001). The square region measures 9° diagonally, and the 10 c/degree grating we appended to the right of the task suggests the limiting resolution of the periphery likely to be invoked. (b) Right: The same stimulus Gaussian blurred so as to barely obliterate the grating, simulating how the stimulus might appear when viewed at a peripheral resolution. Note that in this peripheral view the target becomes fused and is all but obliterated, while other elements elsewhere merge to form false targets. We suggest that those with high periphery-to-center ratio response will be more drawn to these false peripheral targets, reducing the efficiency of their search.

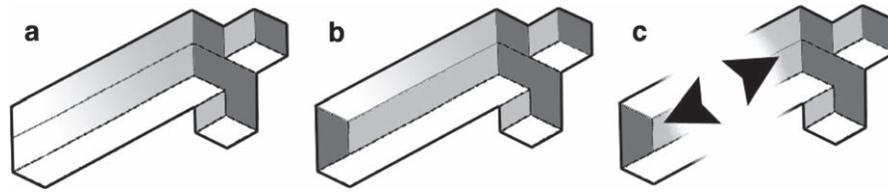


Fig. 3. (a) A logically consistent (possible) rendering of an object. (b) An impossible figure (adapted from von Karolyi, 2001). (c) Impossible figures are characterized by internal inconsistencies in their geometry that are evident when portions of the figure are pair-wise compared. We suggest that peripheral advantages in dyslexia facilitate such comparisons, speeding their response.

dyslexia tend to exhibit peripheral advantages characteristic of a high-PCR group.

Individuals with dyslexia have also been found to exhibit talents for implicit spatial learning (Howard et al., 2006) as measured by the contextual cueing task (Chun & Jiang, 1998). Implicit spatial learning occurs in everyday contexts as a result of repeated exposure to a space that becomes familiar, such as recalling locations of implements stored in a kitchen. A type of task called contextual cueing is used to measure abilities for implicit learning by observing reaction times for finding a T-shaped target randomly placed among a field of L-shaped distracters (see Figure 4a). The task interleaves arrangements that are new and random (novel condition) with patterns seen in previous trials (repeated condition). The arrangement of distracters is learned implicitly while searching for the target, which facilitates target detection in the repeated condition but not in the novel condition. Thus, abilities for spatial learning can be observed by comparing reaction times in the repeated and novel conditions in earlier and later trials of the conditions (Figure 4b).

Studies of contextual cueing in dyslexia show that, on average, people with dyslexia outperform controls in implicit

spatial learning (Howard et al., 2006), despite the fact that their reaction times for the search are slower (see Figure 4b). Given that a process of pair-wise comparisons (suggested by arrows in Figure 4a) is used in learning the locations of the target (Brady & Chun, 2005), we would predict that high-PCR groups, who are more adept at peripheral comparisons (Table 1), will show advantages for spatial learning. At the same time, since a peripheral advantage confounds the search by increasing peripheral distraction, this same group should be slower overall in locating the target. Both these effects are evident in the data of Howard and colleagues, where the dyslexic group was found to be slower at search but stronger at spatial learning, consistent with the notion that dyslexia constitutes a high-PCR group.

SUGGESTIONS FOR FUTURE RESEARCH

The PCR framework suggests a number of potentially fruitful topics for research to elaborate and to test the model. Two relevant arenas for research are (a) the relation of central and

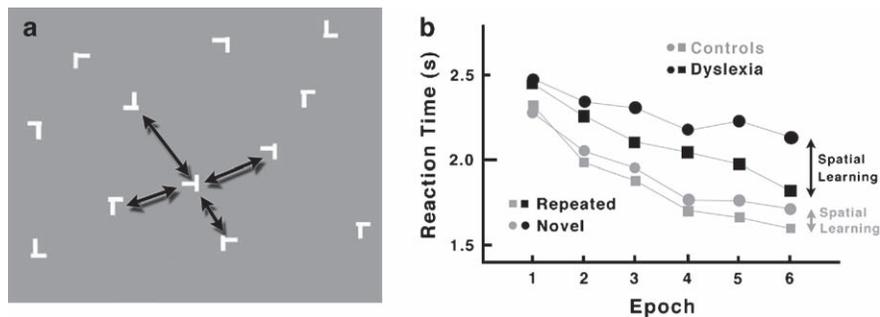


Fig. 4. (a) In the contextual cueing task, subjects are asked to rapidly locate a T-shaped target in a field of distracters. Performing this search, the target location is learned through a process of spatial comparison (suggested here by arrows superimposed on the task). We suggest that these comparisons are facilitated in dyslexia by enhanced peripheral abilities. (b) Spatial learning is measured as the difference in reaction times for repeated patterns compared to novel ones. Dyslexics search novel layouts more slowly but seem to learn the spatial layouts more efficiently. Figures were adapted from Howard et al. (2006).

peripheral vision to search and comparison skills and (b) the connection of visual skills to learning and instruction, especially in students with dyslexia.

Connecting Central and Peripheral Vision to Search and Comparison

The PCR model predicts that any effect that alters the balance between central and peripheral visual perception will yield corresponding effects for visual search and peripheral spatial comparison. There are several ways to test this relation empirically. For example, eye tracking can be used to lock a gaze-contingent window to a computer display, creating artificial scotomas (small areas of reduced visual acuity) that arbitrarily vary the balance between center and periphery (Cornelissen et al., 2005; Henderson, McClure, Pierce, & Schrock, 1997). In this context, the PCR model predicts that abilities for visual search will be seriously compromised by a central scotoma, whereas abilities for peripheral comparisons will actually be enhanced. The exact opposite is predicted when a gaze-contingent tunnel is used to artificially limit peripheral vision. The PCR bias will also be modified by presenting the same task under different lighting conditions (e.g., use of low-level illumination will introduce a peripheral bias, whereas the use of color contrasts will bias perceptual sensitivity toward the center).

The PCR framework also predicts that abilities for visual search and peripheral comparison are negatively correlated, such that individuals who tend to excel in one process (e.g., visual search) will be less adept at the other (e.g., spatial comparison). Studies tracking individual response for each of these abilities may even reveal a bimodal distribution. Depending on the PCR bias of individuals within a given population, we would expect to find that one set of abilities or the other would be favored. For example, if a sample is composed primarily of people with dyslexia (high PCR), then the distribution will more strongly favor processes of spatial comparison.

Investigating Implications for Instruction

In the arena of education, the PCR framework predicts that high-PCR students (such as, presumably, those with dyslexia) should demonstrate very specific advantages and disadvantages for visual learning, including:

- Advantages for concepts dependent on making visual comparisons (e.g., involving symmetry) across a single figure.
- Disadvantages for concepts dependent on visual comparisons across multiple figures (especially if on different pages).

- Advantages for identifying or locating objects embedded in a distracting background, when the background is familiar.
- Disadvantages for identifying or locating objects embedded in a distracting background, if the background is unfamiliar.

The proposition that visual learning strategies differ systematically depending on PCR bias can provide insights to guide the design of visual materials (e.g., figures, graphics, Web materials, multimedia) intended to support instruction. This approach predicts that subtle differences in the context of a visual presentation may affect students' abilities to perceive intended points, depending on their PCR bias. For researchers interested in testing these predictions in an educational context, important factors to consider are the degree to which illustrations make use of visual search (favoring low PCR) versus spatial comparison (favoring high PCR) and the degree to which opportunities for implicit spatial learning are encouraged. Of course, people develop long-term skills for visual search and comparison over long-time periods, and those skills are affected by persistent biases in their use of central versus peripheral visual systems. Therefore, any research investigating the impact of a peripheral visual bias on learning would also need to address the role that development plays in shaping the learning behaviors observed.

To devise supports for students with high-PCR characteristics, investigators can consider pedagogical analogies to tasks, where those with dyslexia tend to outperform controls. For example, findings with the impossible figures task (Figure 3) suggest that those with dyslexia may be adept at spotting departures from symmetry inherent in a figure or a layout. Such abilities can be leveraged to scaffold instructional content and benefit this group. Figure 5 illustrates a paradigm that we are currently investigating in our laboratory, where the inherent symmetry in a scientific figure or graph may promote abilities for scientific discovery among those with better peripheral processing.

Similarly, the contextual cueing paradigm provides clues as to how abilities for spatial learning might be used to support high-PCR learners. For example, spatial learning plays a key role in pedagogy that deals with characterizations of the fundamental properties of matter, as with the spatial layout of elements in a periodic table (Figure 6). We predict that exercises that provide students the time to gain familiarity with the locations of elements in the table (say, by having them hand-graph a portion of the table) will be especially instructive for high-PCR students who can draw upon their relative strengths for spatial comparison.

Clearly, the PCR framework generates a series of predictions that can be useful in educational settings, but at this

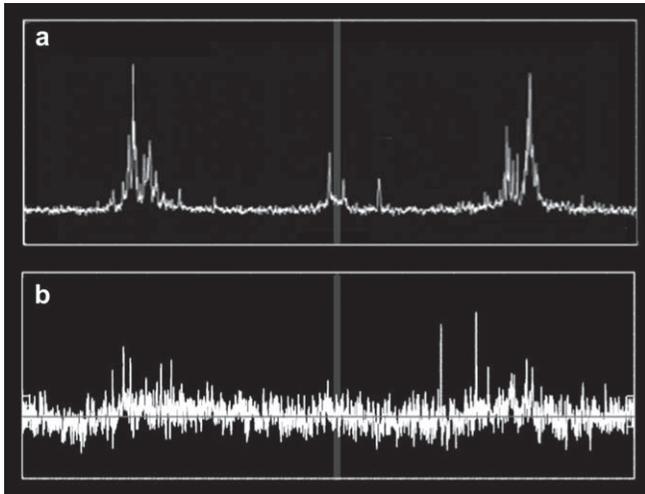


Fig. 5. Those in high-periphery-to-center (PCR) ratio groups may be more sensitive to spatial symmetry present in figures and graphs. For example, (a) shows a graph of the spectrum of a galaxy revealing a characteristically symmetric mirror-image profile believed to be an indication of the presence of a massive black hole. (b) Those in high-PCR groups may be more sensitive to faint hints of such symmetry present in noisy data and thus may be able to detect the presence of black holes at earlier stages in the data-gathering process. Figures were adapted from Braatz, Henkel, Greenhill, Moran, & Wilson (2004) and Kondratko et al. (2006).

characteristics that make them fundamentally distinct. For many reasons, people vary in their abilities to make use of information in one region relative to the other, and this variation tends to bias abilities for visuospatial tasks. Individuals who are biased to favor the center over the periphery are expected to perform well on tasks that depend on visual search but less well on tasks involving spatial comparisons. This performance pattern should be reversed in individuals who have a bias favoring the peripheral field. Top-down attentional processes that cause task load in the center to suppress response in the periphery, and vice versa, will tend to reinforce an initial bias, so that on average, a bimodal distribution in abilities for search and comparison is expected.

Mounting evidence suggests that at least some subset of dyslexics show a bias favoring information in the peripheral field. We contend that this bias contributes to poor performance for temporally sequential visual processes (e.g., visual search), but results in complementary talents (compared to normal readers) for contemporaneous comparative processes such as spatial learning. Experience will serve to increase the effects of this bias, leading to long-term learned behaviors that affect skills and abilities more globally.

point, most of them are only predictions. They all need to be studied empirically before they are implemented in any meaningful way in the classroom.

CONCLUSIONS

The center and periphery of the visual system are distinguished by differences in their anatomical and functional

It has long been suspected that people with dyslexia may have certain visuospatial talents (see discussion in Winner et al., 2001), and it has been noted that many people with dyslexia perform well in visually intensive domains (Wolff & Lundberg, 2002). Indeed, dyslexic individuals, such as the Nobel laureate Baruj Benacerraf, have made remarkable contributions to intellectually challenging fields despite their disabilities (Fink, 2006). We hypothesize that the push-pull between deficits and talents associated with dyslexia is an inherent consequence of the neurology of this disability that

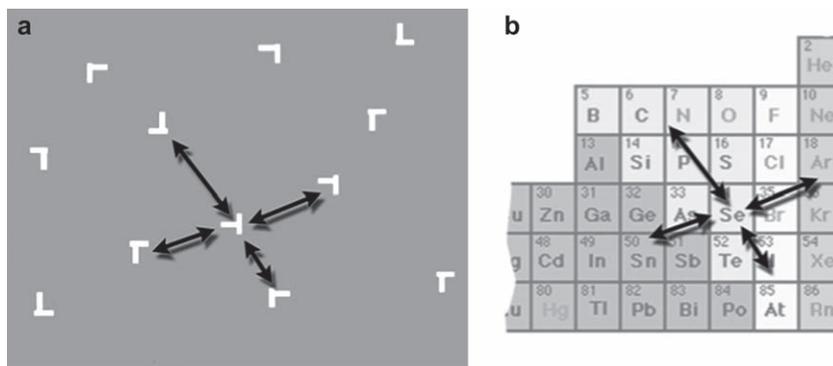


Fig. 6. (a) In the contextual cueing task, enhanced abilities for spatial comparison (suggested by arrows overlaid) can lead to talents for spatial learning in those with dyslexia. (b) Similarly, advantages for spatial learning can promote learning positional relationships among elements in the periodic table, important for building a conceptual understanding of atomic characteristics.

leads to association of developmental dyslexia with advantages for peripheral vision.

The PCR framework put forward in this article predicts that abilities for visual search are, in general, oppositely paired with abilities for spatial comparison, such that those who are good at one will tend to be poor at the other. If corroborated, these findings may have important implications for the development of pedagogical strategies, especially in fields such as science or mathematics where visual representations of concepts are an important part of instruction: Visual strategies that work well for low-PCR students may be less effective when applied to high-PCR students (which we predict would include at least a subset of those with dyslexia). Conversely, high-PCR people may bring capabilities to the learning process that are not shared by their low-PCR peers, providing advantages that, for example, might be used to scaffold learning in students with dyslexia. Given these two different patterns of ability (and disability) for visual learning, instructional approaches can be designed to enhance opportunities for visual learning for people with each pattern.

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NOTE

- 1 One possible way to construct a quantitative definition of PCR would be to use a speed-accuracy trade-off formalism (Reed, 1973) to create a ratio comparing the measured speed of visual processing at 4° and 12°, following procedures of Carrasco et al. (2003).

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