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Psychological Science 2009 20: 1484
DOI: 10.1111/j.1467-9280.2009.02471.x

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Research Article

Visual Parsing After Recovery From Blindness

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ABSTRACT—*How the visual system comes to bind diverse image regions into whole objects is not well understood. We recently had a unique opportunity to investigate this issue when we met three congenitally blind individuals in India. After providing them treatment, we studied the early stages of their visual skills. We found that prominent figural cues of grouping, such as good continuation and junction structure, were largely ineffective for image parsing. By contrast, motion cues were of profound significance in that they enabled intraobject integration and facilitated the development of object representations that permitted recognition in static images. Following 10 to 18 months of visual experience, the individuals' performance improved, and they were able to use the previously ineffective static figural cues to correctly parse many static scenes. These results suggest that motion information plays a fundamental role in organizing early visual experience and that parsing skills can be acquired even late in life.*

Individuals who acquire sight late in life provide a unique window into several aspects of visual development. Such cases, however, are extremely rare; fewer than 30 have been studied in any detail over the course of the past 1,000 years (Valvo, 1971). Through a concerted effort to locate such individuals in underprivileged enclaves in India, a country with an estimated 25% of the world's blind, we have been able to conduct longitudinal studies from sight onset up to 18 months later with 3 such patients, S.K., J.A., and P.B. These studies provide an opportunity to add to this important but sparse body of work (Fine et al., 2003; Gregory & Wallace, 1963; Maurer, Lewis, & Mondloch, 2005; Von Senden, 1932/1960).

Real-world images typically comprise many regions of different colors and luminances (see Fig. 1). The human visual system is adept at integrating subsets of these regions into meaningful entities. How this is achieved is a fundamental question, and has been researched extensively in the domains of experimental and computational neuroscience (Brady & Kersten, 2003; Hummell & Biederman, 1992; Hupe et al., 1998; Marr, 1982; Needham, 2001; Tu, Chen, Yuille, & Zhu, 2003; Ullman, 1996; Wertheimer, 1938). Much of this work has focused on the use of heuristics, such as alignment of contours and similarity of texture statistics (August, Siddiqi, & Zucker, 1999; Field, Hayes, & Hess, 1993; Grossberg & Mingolla, 1985; Kovacs & Julesz, 1993; Leung & Malik, 1998; Mumford & Shah, 1985). In circumscribed domains, these heuristics can account rather well for human performance (Elder & Zucker, 1998; Kanizsa, 1979; Koffka, 1935), but using them for analyzing real-world imagery remains an open challenge (Borenstein & Ullman, 2002; Shi & Malik, 1997). Furthermore, although it is evident that a mature visual system makes use of these heuristics, it is unclear whether they serve to organize visual information during the early stages of development. Determining the nature of the cues that are active at that time is important for elucidating the principles of visual learning and bootstrapping.

Our studies with 3 individuals immediately after they first experienced patterned vision provided a rare opportunity to examine the bootstrapping mechanisms for visual parsing and the progression of visual abilities due to visual experience. These studies were undertaken as part of Project Prakash, our initiative in India to identify, and provide medical care to, individuals with treatable congenital blindness (Mandavilli, 2006). In working with these individuals, we also have an opportunity to examine how time bound the development of parsing skills is, and whether it is subject to a critical period. Earlier case reports have demonstrated that individuals who acquire sight late in life show a profound deficit in interpreting the visual confusion that they suddenly encounter (Fine et al., 2003; Gregory & Wallace, 1963; Valvo, 1971; Von Senden, 1932/

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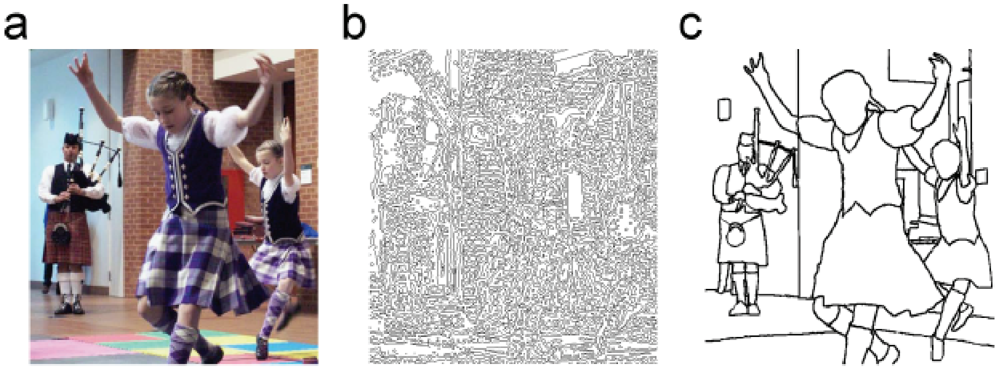

Fig. 1. Example illustrating how a natural image (a) is typically a collection of many regions of different hues and luminances (b). The human visual system has to accomplish the task of integrating subsets of these regions into coherent objects, illustrated in (c).

1960). These results appear to suggest that visual parsing might be subject to a critical period in the first few years of life. Despite the lack of conclusive evidence for the permanence of deprivation-induced deficits, individuals who have been blind past the age of 5 or 6 years but have treatable conditions (a situation that is virtually nonexistent in developed nations, but unfortunately not as rare in the developing world) are often passed over for treatment owing to the assumed poor prognosis for recovery.

It is worth noting that working with a noninfant population provides us with both advantages and disadvantages. On the one hand, because the brain is otherwise almost fully mature in the individuals we work with, visual learning can be segregated from development of the other senses and from real-world knowledge. On the other hand, a mature brain may not undergo the same progression as an infant brain. Thus, it is appropriate to consider this work as complementary to, rather than a replacement for, traditional studies with infants.

METHOD

Participants

S.K. is a 29-year-old male, born in Bihar, India. By the time he was 4 months old, members of his family noticed his inability to fixate and a lack of visually guided behaviors. Because of financial and logistical constraints, medical intervention was not sought until S.K. was an adolescent. At the age of 12 years, he was examined by an ophthalmologist, who recommended surgery to correct his sight. However, the operation was canceled because S.K.'s father had an illness that completely depleted the family's finances. S.K. was admitted to the State School for the Blind in Darbangha, Bihar, where he studied for 12 years and learned Braille. In 2000, he moved to a hostel for the blind in New Delhi and enrolled in a correspondence course; he earned a master's degree in political science in April 2006. It was during a visit to this hostel that we met S.K. in January 2004.

Examinations by three independent ophthalmologists in New Delhi yielded identical assessments: S.K. has secondary congenital bilateral aphakia (B.L. Johnson & Cheng, 1997; Pratt & Richards, 1968), with the lenses almost completely absorbed in the anterior and posterior chambers of the right and left eye respectively. The optical pathways in the eyes are clear. S.K.'s acuity was assessed to be 20/900. He had never been able to afford a pair of eyeglasses that could compensate for his aphakia. During our next visit to India, in July 2004, we had S.K. reexamined by optometrists and ophthalmologists in New Delhi and purchased a pair of eyeglasses for him. Postcorrection acuity was determined to be 20/120. The residual acuity impairment is likely due to neural amblyopia (Kiorpes & McKee, 1999).

Beginning 2 weeks after the refractive correction, we performed a series of experiments to assess S.K.'s visual abilities. Tests of low-level visual function revealed that he had near-normal ability to discriminate among colors, luminances, and motion directions.

We also had the opportunity to work with 2 male children, P.B. and J.A., whom we studied beginning 1 and 3 months, respectively, after surgery to correct their dense bilateral congenital cataracts. P.B. received treatment at the age of 7 years, and J.A. at the age of 13 years. P.B. was born in a village near Panipat, Haryana. His family has a long history of congenital blindness. Both P.B. and his older sister T.B. (age 12) were congenitally blind, as were his father, his paternal grandmother, his great-grandmother, two aunts, and an uncle. P.B. has been enrolled in the Blind Relief Association's school in Delhi since the age of 4½ years. His parents did not pursue treatment for him (or T.B.) because a doctor incorrectly told them that his condition was untreatable because of the development of nystagmus. A botched eye surgery that P.B.'s uncle had undergone a few years earlier further dampened the parents' desire to seek treatment for their children. We came across P.B. in an outreach eye-screening session we had organized in his school. His condition was determined to be treatable. In December 2005, P.B. underwent a small-incision cataract surgery with intraocular lens implantation in both eyes; as a result, his acuity improved from light perception to 20/100.

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J.A. was born in Bijnor, Uttar Pradesh. He has five siblings, three sighted (ages 21, 19, and 8) and two congenitally blind (ages 17 and 7). Both parents are illiterate, and J.A. has never received any education. J.A. received cataract surgery and an intraocular lens implant in both eyes (right eye: September 2005; left eye: October 2005); as a result, his acuity improved from light perception to 20/80.

In what follows, we describe results from all 3 individuals. Practical constraints allowed us to work with S.K. more thoroughly than with P.B. and J.A., preventing us from replicating every experiment from the battery with the children. For convenience, we refer to S.K., J.A., and P.B. collectively as the *recently treated* group.

S.K. volunteered his participation and was not paid, other than being compensated for transportation costs. The families of P.B. and J.A. were compensated for their transportation costs and also for part of the wages they lost while in the hospital. Subjects were free to take as many rest breaks as they wished during the course of the testing. We also enlisted 4 normally sighted adult control subjects. These subjects came from a social tier similar to that of our experimental group and had received a basic education through high school.

Procedure

Tests of Static Visual Parsing

Our studies of static visual parsing comprised seven tests, which assessed the subjects' responses to images of simple shapes. These tests were administered 2 weeks after S.K. received his glasses and 1 month and 3 months postsurgery for P.B. and J.A., respectively. Their task was to say how many objects there were in each image, point to where they were, and (whenever possible) name them. (The recently treated group was already familiar with common shape names through touch.) Figure 2a illustrates the specific tasks and representative stimuli. Tests A, B, F, and G were readministered to S.K., J.A., and P.B. 18 months, 12 months, and 10 months posttreatment, respectively (S.K. was also tested 6 and 12 months posttreatment). Each of the seven tests comprised 10 distinct trials. The recently treated subjects' viewing distance averaged 40 cm. Control subjects' viewing distance was scaled to simulate image information loss in the recently treated group. All stimuli were presented until a response was given.

Test of Object Recognition

For this test, subjects were shown a set of 50 images of common objects and were asked to name the objects they recognized. The images were in color and had different backgrounds (see Fig. 3). The images subtended 25 degrees of visual angle, on average. There were no constraints on viewing time. As were the tests of visual parsing, the recognition test was administered 2 weeks after S.K. received his glasses and 1 month and 3 months postsurgery for P.B. and J.A., respectively.

Tests of Dynamic Visual Parsing

The stimuli used to test dynamic visual parsing were similar to those in the tests of visual parsing, but incorporated motion cues. These tests were administered at the same time as the initial tests of static visual parsing and the recognition test.

RESULTS

Figure 2b shows all subjects' performance in the seven tests of visual parsing. The responses of the recently treated group exhibited a consistent pattern. They had no difficulty in enumerating individual geometric shapes presented by themselves or in the presence of other shapes that were nonoverlapping (Test A). However, when the shapes overlapped, regardless of whether the shapes were presented as line drawings or as filled transparent surfaces (Test B and C), the recently treated subjects' responses were very different from control subjects'. They perceived all closed loops and regions of uniform luminance as distinct objects. All errors we observed were such errors of overfragmentation. Thus, for instance, when viewing two overlapping squares, the recently treated subjects invariably parsed them as three objects. Using lines of different colors or luminances as potential aids for segmenting the component objects did not change this pattern of results. Note that to ensure that these subjects understood the task, we told them at the start that the figures might be overlapping (a notion they were familiar with from prior haptic experience) and that they had to indicate the number of "objects," rather than "regions."

When the images showed opaque overlapping shapes, S.K. was able to correctly indicate their number (Test D), but performed at chance in determining their depth ordering (Test E). Extended contours made up of a series of separated line segments embedded in a field of randomly oriented line segments (Test F) were only infrequently detected by the recently treated subjects. When three-dimensional shapes, such as cubes or pyramids, were shown with surfaces of different luminance consistent with lighting and shadows (Test G), the recently treated subjects reported perceiving multiple objects, one corresponding to each facet. They were unable to integrate the facets into the percept of a single three-dimensional object.

In summary, the recently treated subjects' performance indicated a profound inability to use cues of contour continuation, junction structure, and figural symmetry to analyze the images presented. The subjects' tendency to perceive the stimuli in a fragmented manner was also reflected in their tracings of simple figures (e.g., see Fig. 2c).

Next, we investigated the functional significance of the recently treated subjects' atypical image-parsing skills. Given their pronounced tendency to overfragment images, we reasoned that their ability to veridically segment and recognize real-world images would be compromised. To test this hypothesis, we assessed their naming performance using a set of 50 images of common objects. S.K. was able to recognize only 26% of the

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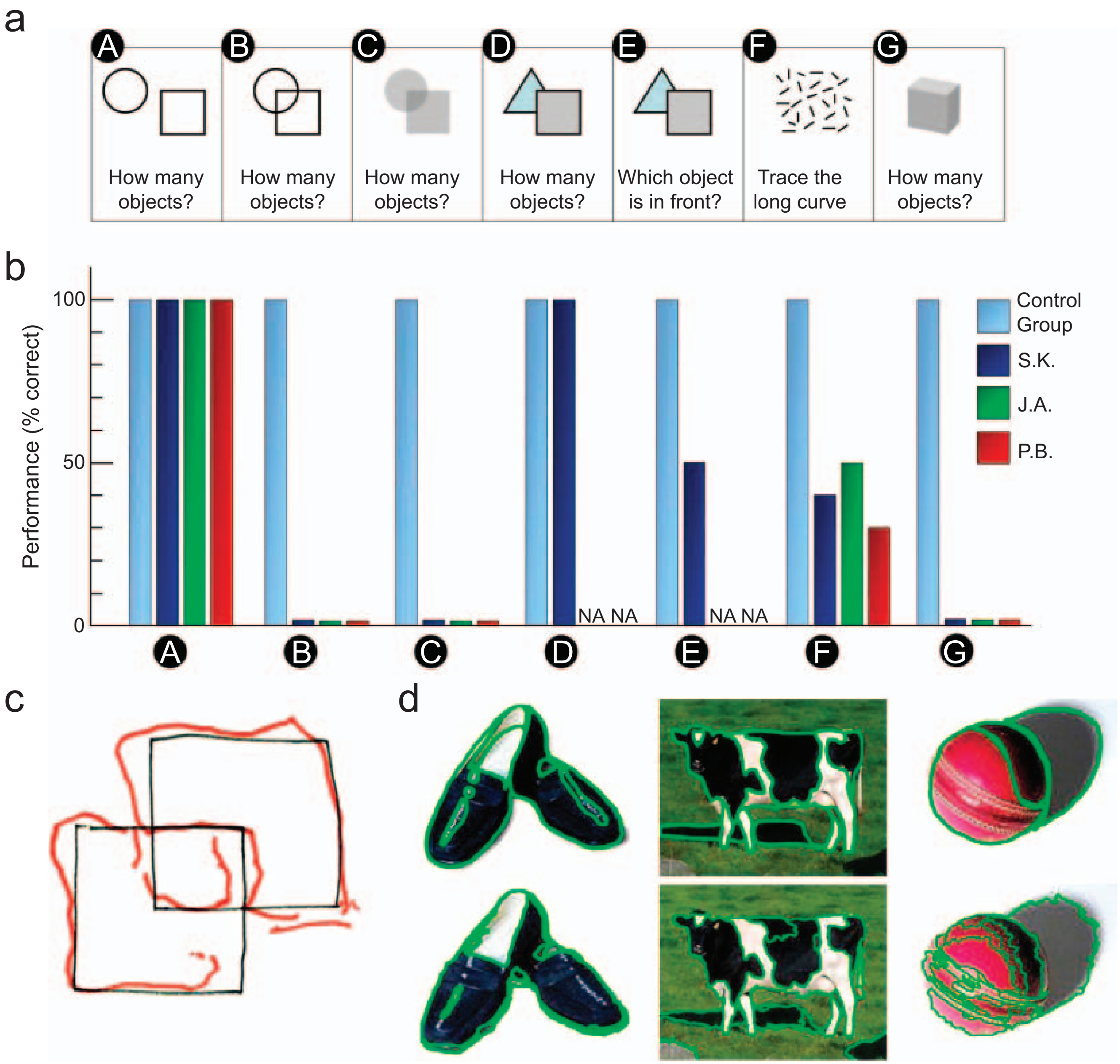

Fig. 2. Subjects' parsing of static images. Seven tasks (a) were used to assess the recently treated subjects' ability to perform simple image segmentation and shape analysis. The graph (b) shows the performance of these subjects relative to the control subjects on these tasks. "NA" indicates that data are not available for a subject. S.K.'s tracing of a pattern drawn by one of the authors (c) illustrates the fragmented percepts of the recently treated subjects. In the upper row of (d), the outlines indicate the regions of real-world images that S.K. saw as distinct objects. He was unable to recognize any of these images. For comparison, the lower row of (d) shows the segmentation of the same images according to a simple algorithm that agglomerated spatially adjacent regions that satisfied a threshold criterion of similarity in their hue and luminance attributes.

images, J.A. recognized 34%, and P.B. recognized only 18%. We asked subjects to point to objects in these images and also to indicate their extent, even if they could not name the objects. We found that subjects' responses were driven by low-level image attributes; they pointed to regions of different hues and luminances as distinct objects. This approach greatly oversegmented the images and partitioned them into meaningless regions, which would be unstable across different views and uninformative regarding object identity. A robust object representation is difficult to construct on the basis of such fragments. Figure 2d, which shows S.K.'s responses to three sample images, illustrates this tendency toward overfragmentation. In separate computational simulations, we found that the recently treated subjects' parsing could be largely accounted for by a simple computational algorithm based on luminance and hue (Fig. 2d, lower row).

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Fig. 3. Motility ratings of the 50 images used to test object recognition and the recently treated subjects' ability to recognize these images. Motility ratings were obtained from 5 normally sighted respondents who were naive as to the purpose of the experiment; the height of the black bar below each object indicates that object's average rating on a scale from 1 (*very unlikely to be seen in motion*) to 5 (*very likely to be seen in motion*). The circles indicate correct recognition responses.

So far, we have described the recently treated subjects' performance with static imagery. In order to make our experiments more representative of everyday visual experience, which typically involves dynamic inputs, we used a set of stimuli that incorporated motion cues (Fig. 4, Tests A and B). The task was the same as for the tests of static visual parsing—to indicate the number of objects shown. The individual shapes underwent independent smooth translational motion. For overlapping figures, the movement was constrained such that the overlap was maintained at all times.

The inclusion of motion brought about a dramatic change in the recently treated subjects' responses. As Figure 4 indicates, they responded correctly on a majority of the trials. Motion also allowed S.K. to better perceive shapes embedded in noise (Fig. 4, Tests C and D). Motion thus appeared to be instrumental for enabling the recently treated subjects to link together parts of an object and segregate them from the background.

The recently treated subjects' recognition results with real-world images, already summarized, provide evidence of another role that motion might play in their object perception skills. When we examined which images the recently treated subjects were able to recognize, an interesting pattern became evident. As illustrated in Figure 3, the recently treated subjects' recognition responses showed a significant congruence with independently derived motility ratings of the objects depicted in the images ($p < .01$ in a chi-square test for each of the 3 subjects). A

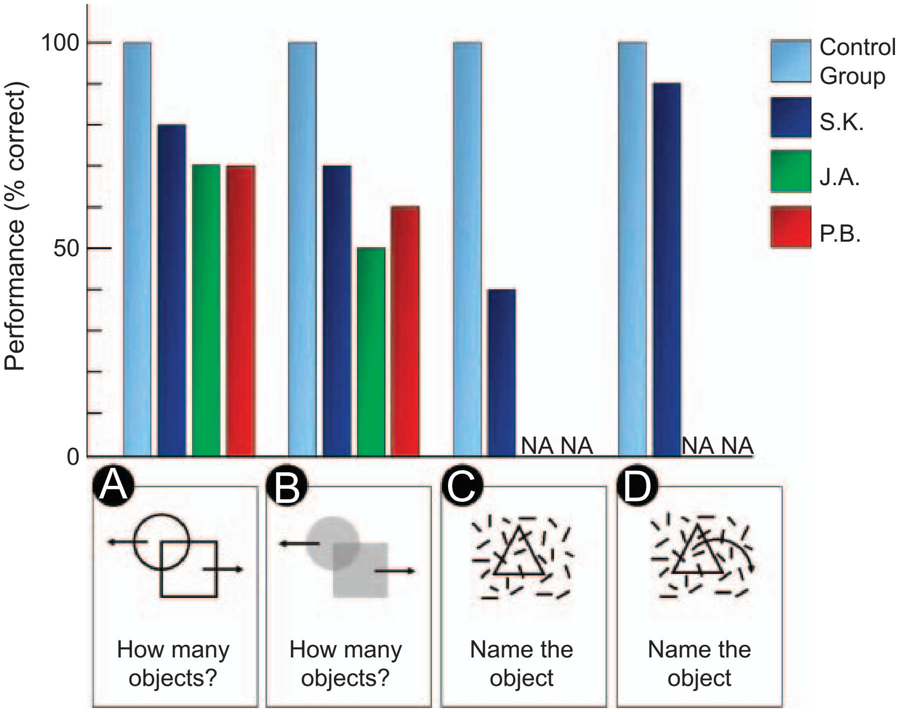

Fig. 4. Recently treated and control subjects' performance on tasks designed to assess the role of dynamic information in object segregation. "NA" indicates that data are not available for a subject. In the illustrations of the four tasks, the arrows indicate direction of movement.

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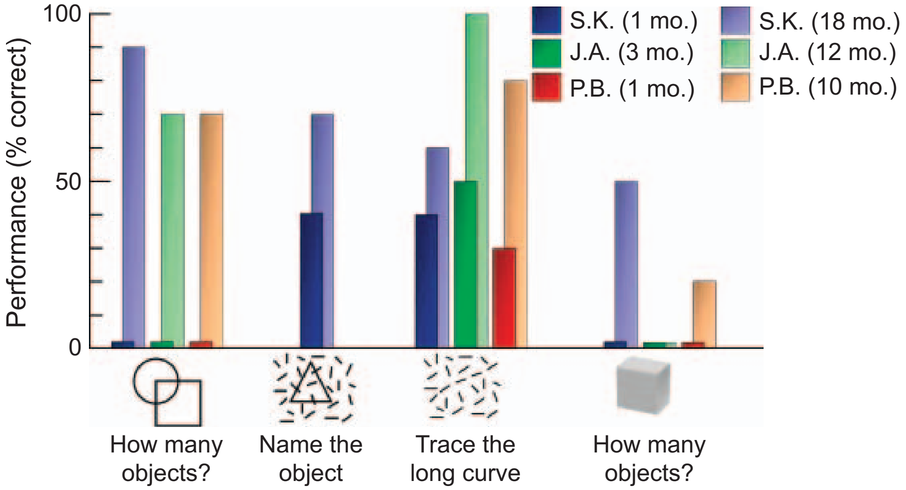

Fig. 5. The recently treated subjects' performance on four tasks with static displays soon after treatment and at follow-up testing after the passage of several months (indicated in the key).

plausible, though not definitive, explanation of this congruence is that motion of objects helps bind their constituent regions into cohesive representations, which can then be used to recognize instances in new inputs that may be static. It appears, however, that motion information is not used to the exclusion of figural cues, as preliminary tests with point-light walkers of the kind devised by Johansson (1973) proved ineffective for conveying the impression of a person: None of the 3 subjects in the recently treated group was able to perceive such displays as anything other than a collection of moving dots.

We also examined changes in the recently treated subjects' performance as a function of time after treatment. S.K.'s performance pattern was unaltered when we tested him 6 and 12 months after treatment. Given the relatively mature age at which he had received treatment, we were not hopeful of observing much visual recovery. However, follow-up tests conducted at 18 months posttreatment demonstrated that S.K.'s visual skills, although still not normal, had registered a significant improvement. The results are summarized in Figure 5. Essentially, at this time, S.K. could perform tasks with static images that he previously could perform only if motion cues were added. As Figure 5 shows, P.B. and J.A. exhibited a similar improvement in their ability to parse static images when tested several months after initial treatment (10 months for P.B. and 12 months for J.A.).

DISCUSSION

Taken together, these results provide a longitudinal glimpse into the development of visual parsing skills several years postinfancy. They suggest that the early stages of this process are characterized by integrative impairments. These impairments lead to perceptual overfragmentation of images, and thus compromise recognition performance. However, the use of motion information effectively mitigates these integrative difficulties. During the early stages of visual learning, motion appears to be instrumental both in segregating objects and in binding their constituents into representations for recognition.

We derive confidence in the generality of the results described here from the consistency among the 3 subjects, and also their congruence with findings from previously reported case studies of sight recovery. Although the earlier studies on sight recovery in adulthood (Fine et al., 2003; Gregory & Wallace, 1963) did not specifically focus on skills involved in region integration, they reported difficulties consistent with impairments in these skills during recognition of natural images. For instance, Gregory and Wallace (1963), in describing their patient SB, wrote: "We formed the impression that he saw [the natural scenes as] little more than patches of colour" (p. 24). Similarly, as regards simple image parsing, Fine et al. (2003) wrote that MM "described two overlapping transparent squares as three surfaces with the central square in front" (p. 915). Furthermore, in these past cases, as in the present one, motion sensitivity was evident soon after treatment.

The privileged status of motion observed with our recently treated individuals is reminiscent of results reported in the infant literature. Although infants eventually become able to use static figural cues for object segregation (Needham, 1998), segmentation from motion arises at least 2 months prior to the ability to segment from static cues (Arterberry & Yonas, 2000; S.P. Johnson, 2003), and infants' ability to link spatially separated parts of a partially occluded object is initially driven strongly by common motion (S.P. Johnson, Bremner, Slater, Mason, & Foster, 2002; Kellman & Spelke, 1983). It is interesting to find this point of overlap between the developmental progressions of infants and of our recently treated group, given that maturational processes would presumably have already completed their time course in our subjects. The neural underpinnings of this similarity are unclear. However, the perceptual utility of an early sensitivity to motion for both popu-

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lations allows a conjecture. It is possible that the early availability of motion sensitivity in the primate brain (Kiorpes & Movshon, 2003, 2004) serves an adaptive purpose by providing a scaffolding for acquiring skills for analyzing static figural information. By observing the correlations between motion-based groupings and static cues, such as aligned contours, the visual system might learn to use the latter by themselves as proxies for grouping (Cavanagh, 1993). This conjecture regarding potential dependencies between early- and later-developing visual skills has significant implications for theoretical models of visual learning (Sinha, Balas, Ostrovsky, & Wulff, in press).

Our experimental results complement past studies of visual development in infancy and after sight restoration. First, they provide evidence that region integration via figural cues is unlikely to be merely a maturational process, unfolding with age, but rather is more likely to be a visually driven developmental process. Second, they highlight the limited efficacy of static figural cues, such as spatially contiguous collinear contours, for purposes of grouping early in the visual-learning time line. These cues have conventionally been assumed to be of fundamental significance for spatial integration (Sigman, Cecchi, Gilbert, & Magnasco, 2001; Ullman, 1996; Wertheimer, 1938). Third, our results provide evidence that motion cues might facilitate the assembly of linked regions that can serve as representations for recognition of new inputs. In this way, our results connect basic grouping phenomena to real-world object recognition. Overall, these results suggest that dynamic information provides a key organizing influence for early visual processing.

The evidence of marked improvement in our subjects' performance over the course of 10 to 18 months suggests that visual skills related to the complex task of image parsing can be acquired even after a prolonged delay, although the rate of acquisition slows down with age, possibly because of decreases in plasticity. Furthermore, the subjects' visual experience during this period derived from their normal daily activities; no special training was provided. Indeed, S.K. resided at a hostel for the blind with no sighted residents to provide instruction. These results, along with a case we have reported previously (Ostrovsky, Andalman, & Sinha, 2006), suggest that the idea of a critical period should not be applied too strictly to visual learning, and provide cause for optimism for the many blind individuals who are candidates for treatment. The human brain, it appears, retains at least some measure of its ability to launch programs of visual learning even after extended periods of visual deprivation. Furthermore, these new insights into the progression of visual skill acquisition point to possible rehabilitative programs for the often-overlooked patients with congenital sight deprivation.

Acknowledgments—The authors wish to thank S.K., P.B., J.A., and their families; the staff at New Delhi's Shroff Charity Eye Hospital; and Richard Held, Beatrice de Gelder, and Scott Johnson. Funding for this work was provided by National Institutes of Health Grant R21 EY015521, the Alfred P. Sloan Foundation, the John Merck Scholars Fund, and the James S. McDonnell Foundation.

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(RECEIVED 12/23/08; REVISION ACCEPTED 3/21/09)

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