Project PRAKÄSH
Development of object perception following long-term visual deprivation

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Understanding how the human visual system learns to perceive objects in the environment is one of the fundamental challenges in neuroscience, and is also the motivation behind a new humanitarian and scientific initiative that we have launched, called 'Project Prakash'. This project involves a systematic study of the development of object perception skills in children following recovery from congenital blindness. We are conducting the experimental part of this study in India where we have located children with treatable congenital blindness. Working in conjunction with recent outreach initiatives by eye-hospitals in India, we have the unique opportunity to help congenitally blind children gain sight and then to study the development of object perception following sight onset. A particular strength of this project is that it affords us an opportunity to continuously follow the development of visual skills and associated neural markers from before the sight restoration treatment to after. Here we provide an overview of Project Prakash and also describe a specific study related to the development of face-perception skills following sight recovery.

The influence of early visual experience on the development of human face processing skills is a topic of much scientific and applied significance, but experimental data on this issue are scarce. A few studies have reported profound impairments in face recognition following early visual deprivation. However, it is unknown how visual deprivation influences performance on the more basic task of face versus non-face classification. Here we report studies with two children, both of whom suffered from congenital blindness lasting at least the first 7 years of life. We assessed their face classification skills following surgical restoration of sight. For one child, the experiments were performed 1.5 months after surgery and for the other, four years post-surgery. Our results indicate that these children are able to detect faces and distinguish them from distracters with high reliability, comparable to control subjects. Furthermore, this ability appears to be based on the use of overall facial configuration rather than individual features – a finding that presents an interesting contrast to the hypothesis of piecemeal processing used to explain impairments in face identification. These results have implications for the nature of face-concept learning schemes in human and computational vision systems.

An Introduction to Project Prakash

Through a process of extensive and continuous exposure, the brain comes to be able to parse complex visual scenes into distinct objects. Several issues about this process remain open. How much visual experience is needed for the development of this ability? What are the intermediate stages in the evolution of object representations? How critical is early visual experience for the development of object perception?

There are two dominant approaches for studying these questions: 1. experimentation with infants, and 2. experiments with adults using novel objects. These approaches have yielded valuable results, but their usefulness is limited by some significant shortcomings. For instance, infant experiments are operationally difficult and the development of object perception processes is confounded with the development of other brain subsystems such as those responsible for attention deployment and eye-movement control. Experiments with adults, on the other hand, are necessarily contaminated by the subjects' prior visual experience, even though the objects used as stimuli may be novel.

We have identified a unique population of children in India that allows us to adopt a very different approach. According to the WHO, India is home to the world's largest population of blind children. While the incidence of congenital blindness in developed nations such as the USA and UK is less than 0.3 per 1000 children, the incidence in India is 0.81/1000. Many of these children have treatable conditions, such as congenital cataracts. However, poverty, ignorance and lack of simple diagnostic tools in rural areas deprive these children of the chance of early treatment. Recently, in response to government initiatives for controlling blindness, a few hospitals have launched outreach programs to identify children in need of treatment and perform corrective surgeries at low cost. These initiatives are beginning to create a remarkable population of children across a wide age-range who are just setting out on the enterprise of learning how to see. We have launched Project Prakash with the goal of following the development of visual skills in these unique children to gain insights into fundamental questions regarding object concept learning and brain plasticity.

Such a population is not available in developed countries such as the United States. Given the extensive network of neonatal clinics and pediatric care in these countries, congenital cataracts are invariably treated surgically within a few weeks after their discovery. Consequently, in the developed world, it is rare to find an untreated case of blindness in a child of more than a few months of age. In India on the other hand, many children with congenital cataracts spend several years, or even their entire lives, without sight. The societal support and quality of life for blind children in India is extremely poor, leading to a life expectancy that is 15 years shorter than that of a sighted child. There is clearly a humanitarian need to help such children get treatment, and a key goal of Project Prakash is to help address this need. Furthermore, in tackling this need, the Project is presented with a unique scientific opportunity.

The scientific goal of Project Prakash is to study the development of object perception following recovery from congenital blindness. We are investigating the time-course of different object-perception skills as assessed behaviorally, the concurrent changes in cortical organization, and also the development of neural markers associated with object-perception. Of special interest to us is face perception, including face localization, identification and expression classification. Few object domains can rival the ecological relevance of faces. Much of the human social infrastructure is critically dependent on face-perception skills. We are studying both the deficiencies and proficiencies of children after onset of sight. The former allow us determine the visual skills that are susceptible to early visual deprivation while longitudinal studies of the latter yield insights about how face-perception develops and what the underlying processes might be.

We call this project 'Prakash', after the Sanskrit word for 'light', symbolizing the infusion of light in the lives of children following treatment for congenital blindness and also the illumination of several fundamental questions in neuroscience regarding brain plasticity and learning.

The broader impact of Project Prakash: The WHO estimates that the number of blind children globally increases by 500,000 every year. Significant advances have been made in pediatric eye-care to counter this problem. Treatments now exist to restore sight in a significant proportion of the afflicted children, such as those suffering from congenital cataracts. However, merely treating the eyes is not sufficient for ensuring restoration of normal visual function. An equally important requirement for sight recovery is that a child's brain be able to correctly process the visual information, after having been deprived of it for several years. Based on past animal studies of the consequences of visual deprivation on subsequent function [Wiesel and Hubel, 1963; Bauer and Held, 1975; Hubel et al., 1977; LeVay et al., 1980; Jacobson et al., 1981], we can expect that the treated children will exhibit visual deficits relative to normally reared children. However, we know very little about what the nature of these deficits will be, and Project Prakash is a step towards acquiring this information. Determining which skills the children are impaired at is crucial for creating effective rehabilitation schemes that would allow the children to be integrated into mainstream society and lead a normal active life. It is important to emphasize that although the patient population for this study will be drawn from India, the results will be relevant to child health in general. Furthermore, the spotlight this project is bringing to bear upon the problem of treatable childhood blindness is likely to strengthen outreach programs not just in India but globally.

Within this broad context of Project Prakash's motivations and goals, we have conducted several specific studies of object perception. Here we report an investigation of face-classification skills following recovery from blindness.

A specific study from Project Prakash: Face classification following long-term visual deprivation

Past work has suggested that early visual deprivation profoundly impairs object and face recognition [Gregory, 1963; Valvo, 1971; Sacks, 1995; Fine et al., 2003]. Even relatively short periods of deprivation, ranging from the first 2 to 6 months of life, have been shown to have significant detrimental consequences on face recognition abilities [Le Grand et al., 2001]. However, we currently lack experimental data that address the more basic issue of the influence of early visual deprivation on face versus non-face discrimination (hereinafter also referred to as 'face classification'), i.e., can face discrimination skills be learned later in life? Results from infant studies of face perception are not too helpful in formulating a hypothesis in this context. While it is generally accepted that visual experience during the first 2 to 3 months of life is sufficient for the babies to exhibit a reliable preference for face-like patterns [Goren et al., 1975; Maurer and Barrera, 1981; Nelson and Ludemann, 1989; Johnson and Morton, 1991; Pascalis et al., 1995], it is not known whether similar learning processes continue to be available later in life. It is possible that long-term visual deprivation might permanently impair an individual's face-classification skills.

In order to investigate face/non-face classification skills following extended visual deprivation, we studied two children, SB and KK, who had both recovered sight after several years of congenital blindness. SB is a 10 year old boy who was born with dense bilateral cataracts. Prior to treatment, he showed no awareness of people's presence via visual cues and could orient to them only based on auditory cues. The cataracts severely compromised his pre-operative pattern vision. He was unable to discern fingers held up against a bright background beyond a distance of 6 inches. By comparison, subjects with normal acuity can perform this task at 60 feet and even an individual with 20/400 acuity, who would be classified as legally blind according to WHO guidelines, would be able to do this task at approximately 36 inches. It is an indicator of the poor state of awareness in rural India regarding childhood blindness, that when SB was brought in to a hospital, it was not to treat his eyes, but rather a leg injury he had suffered after tripping on an obstacle. After having been blind for 10 years, SB underwent cataract surgery in both eyes (the two procedures were a month apart). The opacified lenses were replaced with synthetic intra-ocular lenses (IOLs). Post-operative acuity in SB's eyes was determined to be 20/120, significantly below normal, but a great improvement over his original condition. SB's left eye currently exhibits significant strabismus.

KK is an 11 year old girl, also born with dense bilateral cataracts. Visual deprivation appears to have been severe right from birth since the white reflex in her eyes was pronounced even while she was an infant and KK did not exhibit any visually-guided responses. In tracing KK's family history, we found that her father had also been born with congenital cataracts. Thus, KK's blindness at birth was considered 'destined' (a blind father being expected to have a blind daughter) and no effort was made by her family to seek medical attention. It was only when KK was 7 years old that she happened to be examined by an ophthalmologist visiting her village as part of an outreach program. She was treated shortly thereafter and the opaque lens in her right eye was replaced with an IOL. Current visual acuity in this eye is approximately 20/120. Her left eye is still untreated and provides no useful vision.

With their guardians' permission, we conducted simple experiments to study SB and KK's face/non-face classification performance. The experiments were conducted six weeks post (first) surgery for SB and 4 years post-surgery for KK. Figure 1 shows SB and KK's eyes at the time of the study. SB's strabismus and KK's dense cataract in the left eye are evident in the images.

Figure 1. Views of SB's (top) and KK's eyes at the time our studies were conducted. Both have recovered functional vision in their right eyes. However, SB has significant strabismus in his left eye while KK continues to have a dense cataract in her left eye.

The first set of studies involved discriminating between face and non-face patterns and also locating faces in complex scenes. We also assessed the performance of two age and gender-matched controls with normal vision. Our stimulus set for the 'face/non-face discrimination' task comprised monochrome face images of both genders under different lighting conditions and non-face patterns. The non-face distracters included patterns selected from natural images that had similar power-spectra as the face patterns and also false-alarms from a well-known computational face-detection program developed at the Carnegie Mellon University by Rowley et al (1995). Sample face and non-face images used in our experiments are shown in figures 2a and b, respectively. All of the face images were frontal and showed the face from the middle of the forehead to just below the mouth. Face and non-face patterns were randomly interleaved and, in a 'yes-no' paradigm, the observer was asked to classify them as such. Presentations were self-timed and the images stayed up until the subject had responded verbally. No feedback was provided during the experimental session. The patterns subtended 10 degrees of visual angle, horizontally and vertically.

For the 'face-localization' task, we used natural scenes, containing one, two or three people (a few sample stimuli are shown in figure 2c). Face sizes ranged from 2 to 4 degrees of visual angle. The subjects' task was to indicate the locations of all faces in a scene by touching the display screen with the index-finger. The response was recorded as a 'hit' if the first touch was within a face boundary. Incorrect locations were recorded as 'false-alarms'. Both the number and correctness of responses to each scene were recorded.

Figure 2. The kinds of stimuli we used in our experiments (rows are labeled a-f top to bottom). (a) Images of upright faces (b) Non-face distracters (c) Scenes with front-facing people (d) Blurred upright faces (e) Inverted faces, and (f) Isolated face parts.

As the top row of figure 3 shows, SB and KK exhibited a high hit-rate and a low false-alarm rate on the face/non-face discrimination task, achieving performance similar to that of the age-matched controls. On the face localization task as well, the two groups were comparable. These data suggest that the ability to discriminate between faces and non-faces and also to localize faces in complex scenes can develop despite prolonged visual deprivation. Furthermore, the fact that SB exhibited this performance within six weeks of treatment suggests that face classification abilities develop rapidly after visual onset.

These results bring up the important issue of the nature of information used by SB and KK for accomplishing face-classification tasks. Past work [Le Grand et al, 2001] suggests that individuals with a history of deprivation are impaired at processing faces holistically and instead analyze them in terms of isolated features such as the eyes, nose and mouth. We attempted to determine whether SB and KK's face classification abilities were based on the use of such a piecemeal strategy wherein the presence of a face was indicated by the presence of specific parts. To this end, we performed an additional set of experiments that specifically investigated the use of holistic versus featural information. These experiments used images that were transformed to differentially effect featural versus configural analysis.

We created three stimulus sets. The first comprised low-pass filtered face and non-face patterns. The low-resolution of these images obliterated featural details while preserving the overall facial configuration. The second comprised vertically inverted faces. Vertical inversion is believed to compromise configural processing while leaving featural analysis largely unaffected [Diamond and Carey, 1986]. The third set comprised images of individual features (eye, nose and mouth). These feature images were enlarged so that low-level acuity issues would not confound the recognition results. Sample stimuli from each of these sets are shown in figure 2d-f. The first two sets were used in a face/non-face discrimination task while for the third, the subjects' task was to indicate what the image depicted. A feature-based strategy would predict that performance would be poor with the first set (low-resolution images devoid of featural details), and comparable to controls for the second and third sets.

The results are summarized in the lower row of figure 3. We found that SB and KK performed as well as the age-matched controls on the low-resolution face classification task. However, their performance was significantly poorer with inverted faces and isolated features. This pattern of results strongly suggests the use of overall configural information by SB and KK. Details of individual face parts appear to be neither necessary nor sufficient for classifying a pattern as a face.

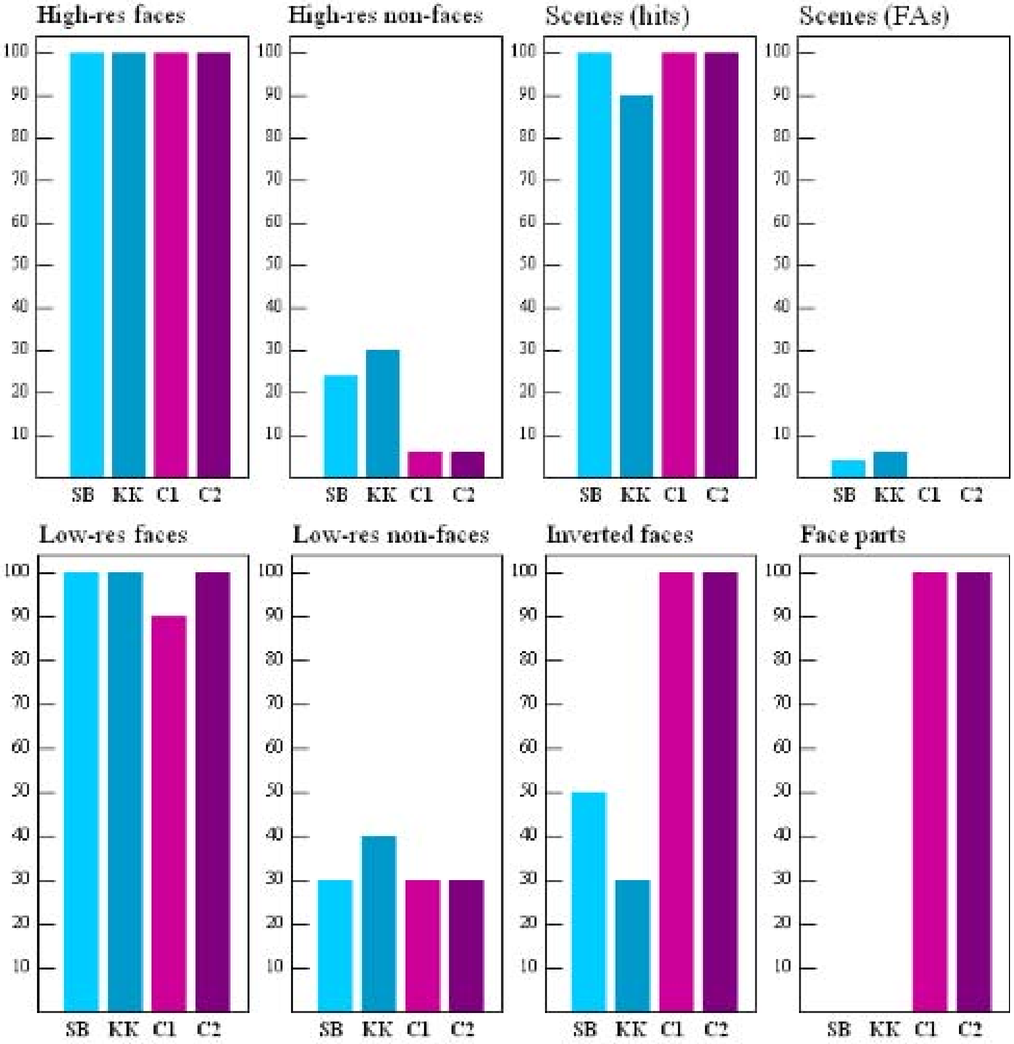

Figure 3. Results from SB, KK and two age-matched controls on various face-perception tasks.

Taken together, our experimental results suggest that children can rapidly develop face classification abilities even after prolonged visual deprivation, lasting from birth for several years. Furthermore, the face concept used for classification appears to encode configural information rather than piecemeal featural details. This particular encoding strategy may well be a consequence of the relatively poor acuity the children possess following treatment for prolonged blindness. Acuity limitations reduce access to fine featural details and may, thereby, induce the use of holistic face information available in low-resolution images.

This finding is also interesting in that it may guide the development of computational models of human face detection skills. Most current models implicitly assume that faces are encoded in terms of their parts (Lee and Seung, 1999; Ullman et al., 2002; Heisele et al. 2003). Face concept learning in these models proceeds by first acquiring facial parts which are then, optionally, combined into a larger representation. This emphasis on the use of face-parts as pre-requisites for face classification, is not reflected in our experimental results. A model that proceeded by developing a holistic face representation without need for featural details, which may be added later as higher acuity information becomes available, would be more congruent with these experimental data.

One way of reconciling our results with past reports of piece-meal processing is by assuming that visual deprivation does not compromise the encoding of overall facial configuration per se, but rather, the ability to discern differences between variants of the basic configuration. This has the consequence of increasing reliance on featural differences for distinguishing one face from another, a characteristic of piecemeal processing.

In considering whether these results have any bearing on the development of face perception skills in normal infants, it needs to be remembered that children like SB and KK differ in many ways from neonates. Unlike the newborn, SB and KK have had extensive experience of the environment through sensory modalities other than vision. This experience has likely led to the creation of internal representations that may well interact with the acquisition of visual face concepts. Furthermore, the deprivation may have led to structural changes in neural organization. For instance, projections from other senses may have claimed sections of the cortex that, in normal brains, would be devoted to visual processing. Thus, a priori, we cannot assume that the developmental courses of face perception in a 10 year old recovering from blindness will have much similarity to that in the newborn. However, some interesting parallels deserve further scrutiny. Primary among these is the quality of initial visual input. Both these populations typically commence their visual experience with poor acuity. The compromised images that result may constrain the possible concept learning and encoding strategies in similar ways. Thus, there exists the possibility that normal infants, and children treated for blindness at an advanced age, may develop similar schemes as a consequence of the similarity in their visual experience. However, the validity of this conjecture needs to be tested via further experimentation.

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