Report

Current Biology

The Limits of Shape Recognition following Late Emergence from Blindness

Highlights

- We test visual perception in children emerging from years of early-onset blindness
- Shape recognition, based on low-level cues, is gained months after cataract removal
- Shape from mid-level cues (shading or occlusion) remains deficient
- Inference-based vision is highly susceptible to long term visual deprivation

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In Brief

McKyton et al. show that early-onset blind children who regained sight only years later learn to discriminate between colors but fail to use 3D pictorial depth cues to recognize shape structure. The putative critical period for acquiring inference-based vision provides further incentive for early treatment of cataracts to restore functional vision.

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The Limits of Shape Recognition following Late Emergence from Blindness

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SUMMARY

Visual object recognition develops during the first years of life [1]. But what if one is deprived of vision during early post-natal development? Shape information is extracted using both low-level cues (e.g., intensity- or color-based contours) and more complex algorithms that are largely based on inference assumptions (e.g., illumination is from above, objects are often partially occluded) [2]. Previous studies, testing visual acuity using a 2D shape-identification task (Lea symbols), indicate that contour-based shape recognition can improve with visual experience, even after years of visual deprivation from birth [3]. We hypothesized that this may generalize to other low-level cues (shape, size, and color), but not to mid-level functions (e.g., 3D shape from shading) that might require prior visual knowledge. To that end, we studied a unique group of subjects in Ethiopia that suffered from an early manifestation of dense bilateral cataracts and were surgically treated only years later. Our results suggest that the newly sighted rapidly acquire the ability to recognize an odd element within an array, on the basis of color, size, or shape differences. However, they are generally unable to find the odd shape on the basis of illusory contours, shading, or occlusion relationships. Little recovery of these mid-level functions is seen within 1 year post-operation. We find that visual performance using low-level cues is relatively robust to prolonged deprivation from birth. However, the use of pictorial depth cues to infer 3D structure from the 2D retinal image is highly susceptible to early and prolonged visual deprivation.

RESULTS

We studied shape discrimination in Ethiopian children suffering from early-onset complete bilateral cataracts (most likely within months of birth). All subjects were operated only years after birth. Shape recognition was assessed using a visual search procedure, requiring the participants ("cataracts," 11 sight-retrieval patients tested days to years after operation [see Table S1], and "controls," 11 matched-control peers) to find an odd target among an array of elements (Figure 1A). Testing consisted of three low-level tasks (requiring discrimination based on color-, size-, or contour-defined shape) and four mid-level tasks (based on 3D pictorial cues: occlusion, shading, and box; or subjective contours: Kanizsa [4]). For more details, see the Supplemental Experimental Procedures.

One major concern is that in the cataracts group, failure in shape recognition may result simply from blurred vision due to uncorrected refraction or amblyopia after prolonged visual deprivation. To ensure that any difference in perceptual capabilities between the two groups did not merely stem from the cataracts group's poor low-level vision, we measured the contrast sensitivity function (CSF) of each of the cataract-treated subjects in an auxiliary experiment. Each cataract-treated subject was paired with a control subject who viewed blurred stimuli of reduced contrast, to best reproduce the specific loss in contrast sensitivity of that cataract-treated subject (see the "Control for low-level deficits" section in the Supplemental Experimental Procedures and Figure S1). The performance of the cataract-treated subjects and their individually matched control subjects is plotted in Figure 1C.

In the low-level tests, most patients identified the target, and there was no significant difference between the groups. On the other hand, cataract-treated subjects' performance on three of the mid-level tasks was significantly deficient compared to the performance of their matched control subjects (one-tailed Wilcoxon signed-rank test: $Z = -2.67$, -2.31, and -2.67; $p = 0.004$, 0.010, and 0.004; effective sample size = 9, 9, and 9 for the occlusion, box, and Kanizsa conditions, respectively). See Figure 1D.

The shading condition was the only test in which many cataract-treated subjects were still able to perform the task above chance. Indeed, the difference in performance level between the two groups was only close to significance ($Z = -1.63$, $p = 0.051$, effective sample size = 10). However, our on-line impression was that unlike control subjects, who typically identify the odd element almost immediately, these cataract-treated subjects seemed to carefully examine each item, looking for local changes in a specific low-level feature to spot the odd man out. If search was indeed conducted in such a manner, a great cost in the reaction time (RT) should be apparent if more elements are to be serially scanned. To test this, the search RT for a target among small and large arrays is plotted in Figure 1E,

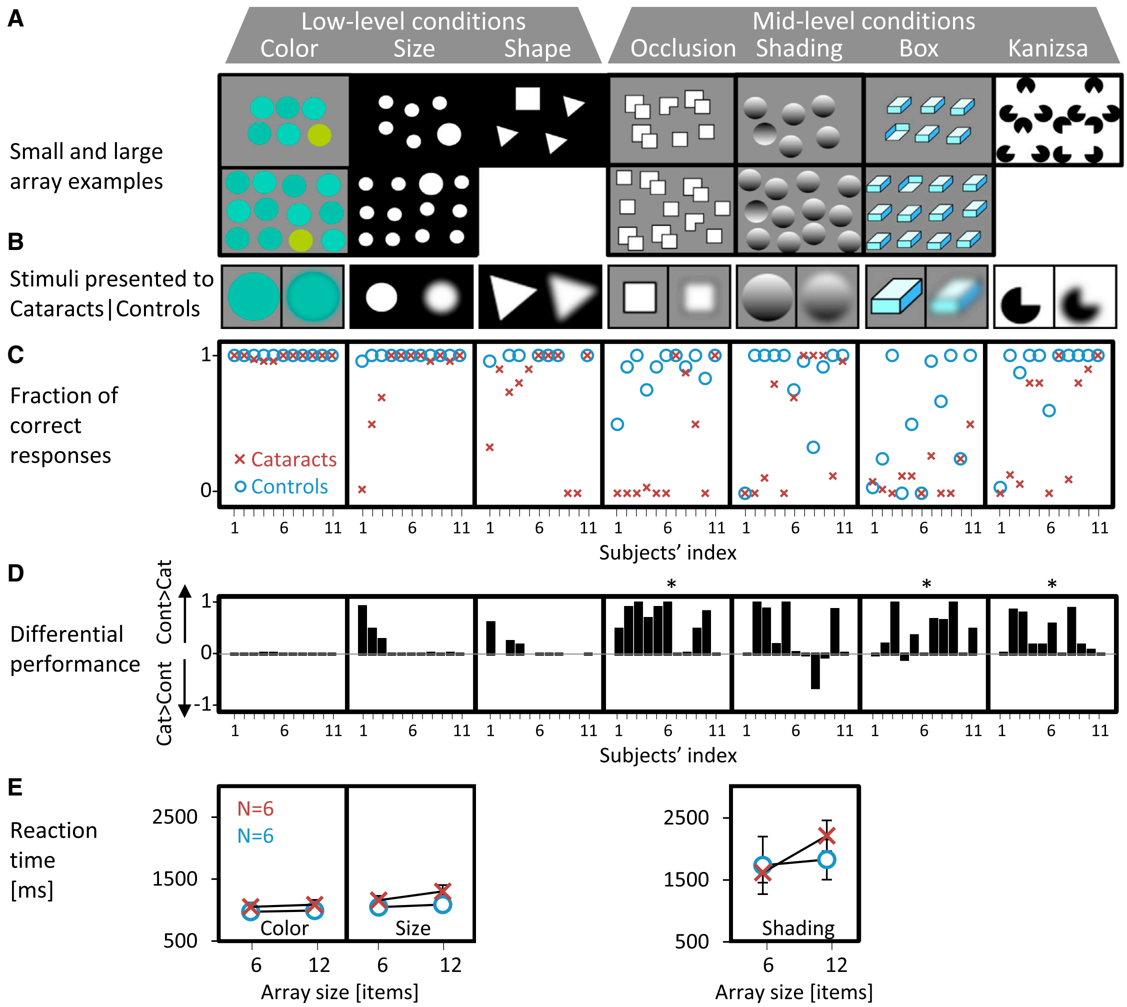

Figure 1. Main Experiment Stimuli and Results

(A) Exemplars of the main experiment stimulus arrays in the various experimental conditions. Note the distinction between low-level and mid-level conditions and the variation in array size in some cases.

(B) Schematic exemplars of the main experiment's stimuli: Stimuli presented to control subjects were blurred at different levels to account for the low visual acuity of the individual cataract-treated subjects (for more details, see Figure S1 and the "Control for low-level deficits" section in the Supplemental Experimental Procedures).

(C) Performance of cataract-treated (red) and their individually matched control (blue) subjects in the main experimental conditions. Subject index is ordered from the worst (1) to best (11) visual acuity according to the cataract-treated subjects' CSF cutoff.

(D) The difference in performance level (Δ fraction correct) between each cataract-treated subject and his/her individually matched control. Positive values correspond to better performance of the control (Cont > Cat). Note that the differences are much clearer and consistent in the mid-level tasks. Asterisks denote significant differences between populations (Wilcoxon test, $p < 0.05$).

(E) Mean reaction time as a function of array size for the six cataract-treated subjects (red) who succeeded (beyond 50%) in the shading condition and their individually matched control subjects (blue) in the color, size, and shading conditions. Error bars indicate the SEM.

See also Figure S1, Table S1, and Movie S1.

for the six cataract-treated subjects (in red) who succeeded (above 50%) in the shading condition (the mid-level condition with the best patient performance). The average RT of their individually matched controls' is plotted in blue. These six cataract-treated subjects were slower in their search (per element) relative to their matched control subjects. Although the results were not quite statistically significant, probably due to lack of power (one-tailed Wilcoxon signed-rank test: $Z = -1.57$, $p = 0.058$, effective sample size = 6), our strong impression is that the cataract-treated subjects shifted to a different (serial) search strategy in this task: each item was carefully examined (e.g., for a decrease in the luminance level along the vertical axis) to spot the odd man out, rather than experiencing a "pop-out" as controls do due to their immediate recognition of 3D shape. To summarize, together, the above results suggest that the use of pictorial depth cues to recover 3D and illusory contour perception are severely impaired following an extended period of early-onset visual deprivation.

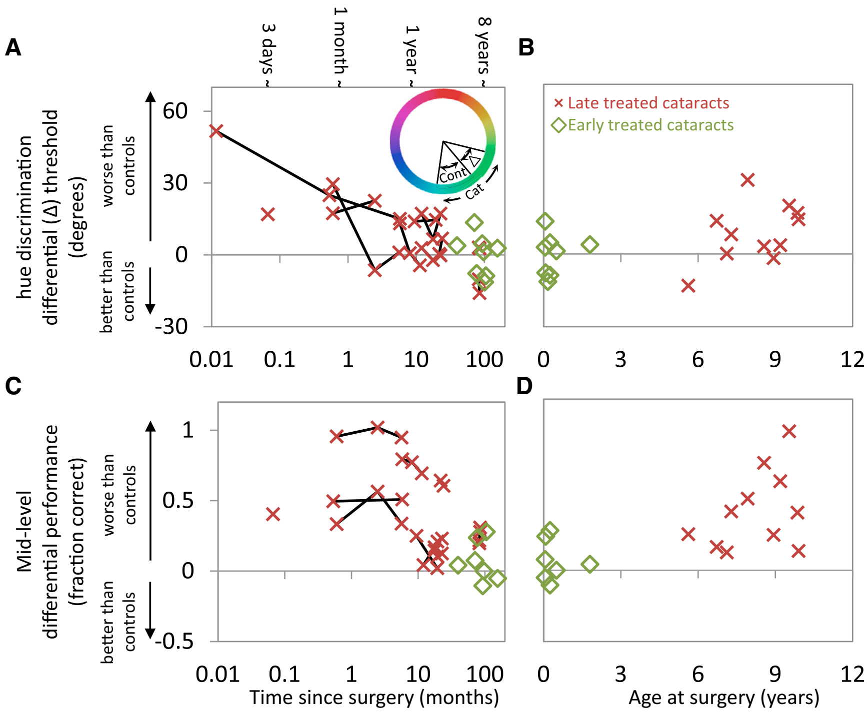

Figure 2. Factors Affecting Hue-Discrimination Threshold and Mid-Level Performance after Surgery

Late-treated subjects are plotted in red symbols, early-treated subjects in green. In all cases, the performance of each subject (cataract treated and control alike) was first age normalized by computation of the residual from that expected from normal child development (see Figures S2C and S2D). Then, the *difference* between performance of each cataract-treated subject and his/her matched peer was computed.

(A) Hue-discrimination differential thresholds as a function of the time past since surgery. The inset depicts for illustrative purposes the threshold of one cataract-treated subject (Cat), the matched control (Cont), and the difference value (Δ). The results of individuals which performed the experiment multiple times are connected by a line. The ordinate is in degrees of hue according to the computer's HSL (hue, saturation, and lightness) values.

(B) The same individual results as in (A) after averaging across repeated sessions are re-plotted as a function of the subjects' age at surgery.

(C) Mid-level differential performance as a function of the time past since surgery. Performance is measured as the fraction of correct responses (averaged across all four mid-level tasks) in comparison with the level achieved by the individually matched control subjects. Positive values indicate that performance is *worse* than that of controls.

(D) The same results as in (C) after averaging across repeated sessions as a function of the cataract subjects' age at surgery.

See also Figure S2 and Tables S1 and S2.

It may be argued that cataract-treated subjects were as good as controls in the low-level tasks (e.g., the color condition) due to the relative easiness of the task (i.e., a ceiling effect). In an auxiliary experiment, we assessed the cataract-treated subjects' hue-discrimination *threshold*. The same odd-man-out task with six elements of colored circles was used, but the difference in hue between the target and the distractors was varied across blocks of trials, allowing assessment of the threshold hue difference per individual (see Figures S2A and S2B). Luminance level was randomized across elements (range, 30–49 cd/m^2) such that the odd target could only be found on the basis of hue differences. Since hue-discrimination threshold improves during normal child development (see the left panel in Figure S2C), each subject's performance level was normalized by comparing it to the age-matched standard performance (see the legend for Figures S2C and S2D).

Figure 2 depicts each cataract-treated individual's hue-discrimination threshold and mid-level performance (across all mid-level tasks) relative to their CSF-matched control after taking into account the expected performance given the subject's age (for full details, see the Supplemental Experimental Procedures and Figure S2). This differential performance is plotted as a function of the time passed since surgery (Figures 2A and 2C) and the child's age at surgery (Figures 2B and 2D). Generally, late-cataract-treated subjects perform worse than their individually matched control subjects in both tasks (Wilcoxon signed-rank test: hue discrimination, $Z = -2.22$, $p = 0.03$; mid-level, $Z = -2.93$, $p < 0.005$). In the hue-discrimination experiment, the performance of the late-cataract-treated subjects steadily improves as a function of the time since surgery (Figure 2A), closing the gap with the sighted peers after less than 1 year. The data are less clear regarding the dependence on the age at surgery (Figure 2B). Indeed, a multiple regression model of the cataract-treated group's hue-discrimination thresholds ($F(2,8) = 6.71$, $p = 0.019$, $R^2 = 0.627$) shows that the time since surgery (in logarithmic scale) can account for a significant proportion of the variance ($p = 0.017$), but the age at surgery does not ($p = 0.485$). Similar improvement in another low-level task during the months following surgery has recently been shown for the identification of simple 2D objects (Lea symbols) based on luminance-defined contours [3], in which both threshold contrast and spatial resolution improve with time.

As for the mid-level vision functions tested here, we found no dependence of performance on the time following surgery (Figure 2C), nor was there any clear dependence on the age in which the cataract-treated subjects were operated ($F(2,8) = 1.01$, $p = 0.40$, $R^2 = 0.202$; time since surgery, $p = 0.52$; age at surgery, $p = 0.39$).

We also tested a group of Israeli subjects (mid-level experiment, n = 7; hue experiment, n = 8) who had congenital bilateral cataract and were operated within months after birth (Figure 2, green symbols). These children had a long period of visual experience (many years). This early-cataract-treated group did well in both tasks (though we may have missed subtle deficits since most reached a ceiling effect). Since both factors (age at surgery and time since surgery) covary and performance shows little variation across these early-cataract-treated subjects, this group does not shed much light on the relative importance of each factor in determining visual function.

DISCUSSION

We studied a unique group of patients that suffered from an early-onset manifestation of bilateral cataracts and were treated only years after birth. These newly sighted children were able to recognize an odd object within an array based on simple 2D cues. Similar to their normally sighted peers, when the target was defined by a unique low-level visual cue (e.g., color-, size-, or luminance-defined shape), their RT hardly increased with the array size. However, they were clearly deficient, in comparison to their sighted peers, when static mid-level visual routines (e.g., extracting shape from pictorial depth cues and illusory contours) were required to identify the target element. Generally, this deficiency did not improve within the first 2 years after surgery. The elapsed time since surgery was not a factor in determining mid-level vision capabilities. Still, most of our data were collected during the first 2 years post-operation, and we tested only a few mid-level routines (mainly using pictorial depth cues). Thus, we cannot rule out the possibility of recovery of some mid-level visual functions after many years of visual experience.

Maybe it is not too surprising that the newly sighted can distinguish between colors or size/shape differences based on luminance contours soon after surgery. It is commonly held that we are born with the rudimentary structural formation allowing for low-level vision [5]. Here we show that this neural structure retains its functionality even in individuals in which only scattered light reached their retinas during early childhood. On the other hand, extracting shape from mid-level cues is a totally different task. Surfaces can produce very different retinal images, depending on the illumination angle, being shaded by themselves or by other surfaces. Mid-level vision deals primarily with the recovery of surfaces despite such dramatic changes in their physical appearance. Behavioral studies in infants show that most stationary mid-level cues are understood only at about 6 months of age [6, 7]. Infants that had suffered from visual deprivation during these critical months are somewhat impaired in tasks requiring completion of Kanizsa shapes [8]. Here we show that years of visual deprivation can hamper this capacity, as well as perception based on other static pictorial depth cues that are likely to tap the ventral stream.

Until now, only a few case studies explored object perception capabilities in the newly sighted. These included subject MM, who was blinded at the age of three, regained vision only at the age of 46, and was tested months later [9]. Other patients were surgically treated and tested through the pioneering initiative of Pawan Sinha (Project Prakash): SRD was presumably blind from birth, regained vision at the age of 12, and was tested 20 years after surgery [10], and subjects SK, JA, and PB regained sight at the ages of 29, 13, and 7 years, respectively and were tested months later [11]. All of these patients had no problem matching or identifying simple 2D shapes. Similar to our results, all those tested with the Necker cube (four out of five) could not identify it as a 3D object. MM, who was the only patient that was tested on Kanizsa shapes, could not fill in the illusory contours and failed to see the resulting square. The results regarding shape from shading and occlusion were somewhat more complicated to generalize. All patients were shown 2D shapes in which one object occluded the other. MM was asked which object was in front of the other, whereas SRD was asked to count the objects. Both succeeded in their task. The rest (three out of five) failed to answer both questions. Understanding occlusion relationships might therefore require either functional vision in the first few years of life (MM) or decades of visual experience (SRD; although counting of objects does not necessarily require the realization that some objects occlude each other). Finally, MM spotted the odd object based on shape from shading and, similar to our patients, MM failed to show automatic pop-out. To summarize, our current findings are generally in line with earlier case studies that hinted that mid-level visual functions might be affected by long-term visual deprivation.

Our current work may also explain why earlier case reports clearly showed that individuals who acquire sight late in life show a profound deficit in integrating the myriad visual features in the scene into a coherent visual scene [9, 12–16]. For example, patient MM reported that scene interpretation was extremely difficult, and if it is achieved, it is done by use of explicit cognitive strategies (e.g., what is the most likely interpretation for this blob, given the circumstances). It is commonly held that object constancy (e.g., recognition of an object as the same as previously seen, despite changes in the illumination angle, shading, occlusion, rotation, etc.), a key characteristic of our vision that is so clearly lacking in MM, probably cannot be established without mid-level vision [17]. Similarly, SK, JA, and PB, who regained sight late, were all unable to utilize cues such as contour continuation, junction structure, and figural symmetry to recognize shapes [12]. They also were poor at naming images of common objects. When asked to point to potential objects, they tended to over-segment objects into meaningless regions which had similar hues or luminance levels. Obviously, since these regions vary according to the direction of illumination and viewing angle, one fails to generate an invariant object representation on the basis of such fragments.

We find a great degree of variation in the treated children's visual capabilities. Some walk into a room without any help and can bypass obstacles such as chairs or tables, but others use their hands to guide them. Almost all of the children can make a visually guided grasping movement in an effort to catch a colorful balloon and throw it around. None of them, however, perform these tasks as gracefully as a normal child. Currently, we are unable to provide a good explanation for the source of the large differences in performance among our patient population. However, we can suggest some ideas, pointing to some likely directions based on our subjective observations. First, some of the children may have had residual vision in the months following birth, such that full blindness developed only later in time. Second, some residual vision may have been possible even prior to the surgery. Typically, the children's vision, prior to surgery was only crudely assessed. Clinically, vision was categorized by the treating ophthalmologist in ascending order from having mere light perception, seeing hand motion, and finger counting from X meters. The patients' pre-surgery vision, even if defined merely as light perception, could still vary considerably between subjects (e.g., different thresholds for light perception, residual vision in the periphery, etc.). Third, clinically, some surgeries are probably more successful than others. Fourth, unfortunately, in most cases, we do not even know for certain the age of the children as it is not in any formal record. Better tools for assessment of all these potential factors for variability are obviously in need.

To summarize, Sinha and colleagues have studied a number of late sight-retrieval patients, focusing on the patients' ability to perform perceptual tasks under naturalistic conditions [10, 11]. Thus, many of their tasks could be solved using low-level cues (even if that isn't how people normally solve the task). Fine et al. used carefully controlled stimuli, but this was a single case study with a subject that had vision almost until age four [9]. This work bridges across those two studies, showing that pictorial depth cue perception and illusory contour completion, which are typically based on learned inference assumptions (e.g., illumination is from above, contours are often partially occluded, etc.), are not spontaneously acquired post-operation. If further natural experience or a targeted learning effort cannot change this condition, (as suggested from the case of MM, tested 10 years later [18]), it may indicate that at least some mid-level vision functions can only be acquired within a critical period of development. We acknowledge, however, that this can only be proven by further showing that a prolonged period of visual deprivation *late* in life does *not* cause the same deficits (as suggested by one previous case study [19]).

Finally, late-sight-retrieval patients might be impaired in the mid-level tasks since these stimuli are more amenable to visual crowding than low-level, simple stimuli [20, 21]. Crowding, generally defined as the deleterious influence of nearby contours on visual discrimination, is a major bottleneck for object perception and is more potent in people with amblyopic vision. Crowding can be seen at the level of simple features (e.g., low-level vision) and also at the level of integration or interpretation of the features (e.g., face recognition, showing holistic crowding). It dramatically reduces the ability to identify a target, especially when it is identified on the basis of complex rather than simple features. Children are much more impaired by crowding than adults, even when their acuity is fully developed. Learning is known to lead to shrinking of the spatial extent of crowding. It therefore seems reasonable that the newly sighted might show greater crowding effects than their peers. However, crowding is relatively weak when the flanking elements all share a common feature, such that they can be grouped together and apart from the target object. Also, crowding is much more pronounced when the stimuli are presented in the visual periphery. In our study, the stimuli were shown until the participants responded, leaving them ample time to make multiple fixations on the visual elements on the screen, thereby allowing their analysis with foveal vision that is relatively crowding free. We therefore suggest that crowding may have *amplified* the late-treated subjects' difficulty utilizing mid-level visual routines, but it is probably not the core problem. Further experiments are required to clarify this issue.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures, two figures, two tables, and one movie and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2015.06.040.

AUTHOR CONTRIBUTIONS

E.Z. and A.M. conceived and designed the experiments together. A.M. wrote the software for the behavioral tests and analyzed the data. E.Z. and A.M. did the testing in Ethiopia and wrote the paper together. R.D. was responsible for testing the early-operated children in Israel. I.B.Z. was the ophthalmologist responsible for all clinical aspects, including medical and optometric examinations and surgeries. He supervised the work of the local Ethiopian crew during most of the surgeries.

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