TACTILE-VISUAL CROSS MODAL TRANSFER AFTER AN EXTENDED PERIOD OF CONGENITAL BLINDNESS

A thesis presented to the graduate faculty of New England College of Optometry in partial fulfillment of the requirements for the degree of Master of Science

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ABSTRACT

PURPOSE: In the underdeveloped villages of India, infants with severe congenital cataracts often do not undergo cataract surgery due to social and economic reasons. Consistent with a strict interpretation of the critical period, if congenital blindness due to cataracts is treated within a few months of birth it usually leads to a near normal development of vision but after age 6 or 7 years there should be little or no improvement. Recent studies have assessed the ability of newly sighted cataract patients in India to visually recognize an object that was just examined by touch. These studies showed little transfer from touch to vision immediately after sight onset but the link between touch and vision developed over time. The objective of Experiment 1 is to assess the development of the tactile-visual link compared to intramodal tactile and visual object recognition while Experiment 2 assesses the precision of the tactile-visual linkage.

METHODS: Subjects were between 8 and 15 years old. In Experiment 1 Lego and curvature objects were used to assess tactile-to-tactile, tactile-to-visual, visual-to-tactile, and visual-to-visual transfer in three patients. In Experiment 2, objects of a specific length, aspect ratio, or

curvature ratio were used to assess the precision of tactile-to-visual transfer in three other patients and four normally sighted control subjects.

RESULTS: In Experiment 1, tactile-to-visual transfer accuracy pre-operatively was about 20% and improved to above 50% during one week. In Experiment 2 the patients had a preoperative error range of 23-51%. There was a 25% improvement on post operation day 1 and by the day 4 there was a 50% improvement in the number of errors.

CONCLUSION: We have demonstrated that the link between touch and vision strengthened significantly after the classic critical period.

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INTRODUCTION

Early Visual Recovery from Congenital Cataracts

Dense congenital cataracts are removed within a few months after birth in developed nations. It is widely believed that early surgical intervention for bilateral congenital cataracts leads to better visual outcomes (Birch, Cheng, Stager Jr., Weakley, and Stager Sr., 2009; Bradford, Keech, and Scott, 1994; Jain, Ashworth, Biswas and Lloyd, 2010, Lambert, Lynn, Reeves, Plager, Buckley, and Wilson, 2006). Congenital cataract patients from the underdeveloped villages of India often do not undergo cataract surgery soon after birth due to lack of education, medical resources and the cost of surgery. Instead these children remain blind for many years.

Birch et al (2009) reported that early surgery for dense bilateral congenital cataracts leads to minimization of deprivation amblyopia. Patients who had cataract surgery performed during the first four weeks of life had lower prevalence of strabismus and nystagmus than surgery after fourteen weeks. One caveat is that surgery during the first four weeks of life resulted in a higher prevalence of secondary membrane formation and glaucoma. Within the first fourteen weeks of life, there is a linear relationship between delay in surgery and visual acuity measurements. There is, in fact, loss of one line of visual acuity for every three weeks of delay. Between fourteen to thirty one weeks of age, there are fewer adverse effects when surgery is delayed. These factors should be considered to determine the optimum timing of surgery.

The latent period in unilateral deprivation in neonates is presumed to last till about six weeks of age and time of surgery during this period does not affect eventual visual outcome. The latent period is followed by the critical or sensitive period of cortical plasticity which lasts for 7 to 8 years. During the critical period episodes of minor visual impairment can affect final visual function. However the effect of any adverse event is less marked with increasing age. For binocular deprivation the latent period has been more difficult to determine. It is presumed to last for 10 weeks. Birch et al (2009) did not find a latent period in their study in children with dense bilateral congenital cataracts and they recommended early surgery to minimize the risk of amblyopia. However, Jain et al (2010) reported that the latent period does exist. Their results indicate there is an exponential decrease in visual acuity with initial age at surgery.

Bradford et al (1993) highlighted the preoperative and postoperative findings in children with congenital cataracts. They found that preoperative nystagmus was present in almost all patients who were having late surgery. However nystagmus was not a reliable prognostic indicator of poor results. Most of these patients showed good postoperative visual acuities. Interestingly a few patients who had early surgery had no preoperative nystagmus but developed postoperative nystagmus. These patients also showed better results compared to other studies cited in this article. Of note some other complications of surgery at a young age included glaucoma, pupillary membranes and amblyopia. In spite of these complications, Bradford et al show that early surgery leads to better visual recovery.

Jacobson et al (1981) assessed visual acuity serially during the first year of life using a preferential looking technique in four infants with congenital cataracts who had their cataracts remove in both eyes before 2 months of age. Visual acuity developed rapidly and attained levels normal for their age. An infant with unilateral congenital cataract had cataracts removed relatively late compared to the bilateral cataract infants. Surgery on the unilateral cataract patient was performed at 11.5 weeks of age. Yet the development of visual acuity was rapid and both eyes became nearly equal by 27 weeks of age. The results of infants with bilateral and unilateral congenital cataracts show that visual resolution is limited at birth but shows remarkable recovery at a rapid rate. Therefore, the period of binocular form deprivation in the form of bilateral congenital cataracts from birth until about 2 months of age showed no long-lasting detrimental effects on the development of visual acuity.

Maurer et al (1969) examined the visual acuity of infants who had been deprived of patterned visual input by unilateral and bilateral congenital cataracts. The patients were 1 week to 9 months of age. The results showed that visual acuity does not improve until the brain receives patterned visual input. For 9 month old infants with congenital cataracts, acuity remains at the newborn level until vision is restored through cataract surgery. Visual acuity measurements were taken 1 hour, 1 week, and 1 month after patch removal and contact lens insertion after cataract surgery. Improvements occurred more rapidly after binocular deprivation rather than monocular deprivation. However, testing 1 month after surgery indicated that monocular cataract patients had improved to the same level as binocular cataract patients. This study showed that visual input is necessary for improvement

of visual acuity and this input initiates rapid development of visual function (Maurer, Lewis, Brent, and Levin 1999).

A retrospective study was carried out to assess whether useable visual acuity is achievable in children with unilateral congenital cataracts. LogMAR acuity of 0.6 or greater represented useable vision in this study. Two thirds of the children who had the operation for congenital cataracts did not develop acuity better than LogMAR of 0.6. Children who had their congenital cataracts removed at an earlier age had a chance of achieving good vision but the results varied and a majority of the patients were strabismic (Allen, Speedwell and Russell-Eggitt, 2009). Lewis et al (1986) measured Snellen acuities of 12 children with unilateral congenital cataract. The children who had the shortest periods of deprivation and who had the normal eye patched close to 50% of the waking time had the best Snellen acuities while the children with longer periods of deprivation and/or little or no patching of the normal eye had poorer acuities.

Magnusson et al (2002) examined the long term effects of age of cataract surgery on visual acuity. They measured visual acuity on patients between preschool age and puberty. They showed that patients who had cataract surgery within the first 7 weeks of life showed a rapid development of visual acuity and higher visual acuity values at age 4 compared with patients who had cataract surgery between 7 weeks and 1 year. Brent et al (1986) examined the visual acuities of patients with unilateral congenital cataracts and concluded that visual deprivation does not prevent the development of good visual resolution provided the deprivation is short.

The studies above provide strong evidence that a shorter period of early visual deprivation leads to better vision. If a patient with congenital cataracts has cataract surgery within a few months after birth, visual acuity develops rapidly and attains levels normal for their age. The brain shows great plasticity in the early months so that sensory experience can repair the effects of sensory deprivation.

Neural Recovery after Monocular Deprivation

Neuroplasticity is the concept used to try to explain the neural or behavioral changes that occur during recovery from neural insult. It is simply the ability of the nervous system to reorganize its structure, function and connections, and it works at many levels from molecular to cellular to systems to behavioral. Neuroplasticity is now being studied in relation to brain trauma, stroke, mental and addictive disorders, neurodegeneration and aging, and pediatric and developmental disorders as well as recovery from different types of amblyopia (Cramer et al, 2011). Most of these recovery processes occur well after the "critical period for plasticity."

Visual pattern deprivation early in life has been used as the primary procedure for studying neuroanatomical and neurophysiological changes in the visual system due to environmental manipulation. This model is very similar to the real life visual conditions that blind children with congenital cataracts endure.

Hubel and Wiesel (1970) in a brilliant series of experiments showed that sensory deprivation induced neural losses associated with deprivation amblyopia only during a

limited time window, “the critical period for plasticity.” They concluded that after the critical period neuroplasticity was not possible. However, many have shown using the same type of experiments that significant change is possible well after the critical period. At the behavioral level Dews and Weisel (1970) showed that kittens with monocular deprivation or strabismic amblyopia were able to recover vision long after the critical period and demonstrate near normal levels of resolution visual acuity with the previously unresponsive eye. Ganz et al (1972) showed that monocularly deprived kittens that have partially recovered from severe amblyopia have relatively good resolution acuity but have difficulty learning to discriminate between objects and have little or no interocular transfer of learned object discriminations. This suggests that the recovered vision is not efficiently used, probably because the nature of the visual input from the recovered eye is so different from that of the normally reared eye that the subject does not recognize what it is seeing with the recovered eye.

Most visual deprivation experiments are performed with monocular deprivation because binocular deprivation leads to relatively weak neural losses in the primary visual system. In line with this, Hylvarinen et al (1981) showed that monkeys reared in darkness for almost a year had relatively small losses in the primary visual cortex. However, key areas for visual-motor coordination in the posterior parietal lobe were taken over by somatosensory inputs with intermodal suppression of visual input and the monkeys appeared to not use their vision at all to aid their mobility. Recovery was disappointing for animals deprived for such a long period.

Many experiments have shown that much of the visual loss seen in deprivation studies is due to GABAnergic inhibitory networks rather than rewiring of information channels in the sensory system. This explains the dominance of the somatosensory input over that of the visual input in the parietal lobe of Hylvarinen's monkeys. Mower et al (1984) and Duffy et al (1985) used GABA antagonists (bicuculline and naloxone) to demonstrate the release of the visual cortex of cats with monocular deprivation and strabismic amblyopia from interocular suppression and the cortex's ability to regain visual responsiveness to the amblyopic eye long after the critical period. Scores of others studies confirm the basic observations described in the studies described above.

The present study examines neuroplasticity in response to treatable forms of visual deprivation, specifically congenital cataracts. The underlying question is whether functional vision can be regained in children who have been blind for many years due to bilateral congenital cataracts and how the children accomplish their recovery.

Congenital Cataracts in India

According to the World Health Organization, India with its huge population has the largest percentage of blind people. Most of these are correctable forms of blindness involving uncorrected refractive errors and untreated cataracts (Ostrovsky, Andalman, and Sinha, 2006). A rare subset of patients who have not been treated for congenital blindness is currently being studied in India by Dr. Pawan Sinha and his research team. Dr. Sinha is a professor and researcher at the Brain and Cognitive Sciences Department at Massachusetts Institute of Technology. He is the founder of "***Project Prakash***", an initiative to search for

congenitally blind children in India, treat the children whose blindness is correctable, and study their visual development (Sinha, 2003 & 2010).The research described in this thesis was performed as part of Dr. Sinha's research program in India.

Children who fit our criteria are found either through eye camps or door to door visits by project volunteers and doctors. They are then brought to Dr. Shroff's Charity Eye Hospital in Delhi, cataract surgery is performed and longitudinal studies are initiated to monitor their progress.

The studies discussed earlier emphasize that a shorter period of visual deprivation leads to better vision. The aim of the present study is to examine whether recovery of functional vision is possible after many years of congenital blindness. For this thesis we studied the ability of patients to perform intramodal and intermodal recognition of objects during the week of cataract surgery.

Tactile to Visual Cross-Modal Transfer by Recoering Congenital Cataract Patients

More than 300 years ago, an Irish scientist and politician Molyneux asked the question whether immediately after a blind man regains his sight, can he without touching a cube and a globe be able to distinguish them purely by sight. In other words, can a former blind patient who is newly sighted identify by sight the objects they experienced only by touch. This is an example of cross-modal transfer which involves some type of interaction between two different sensory modalities—vision and touch. Molyneux's specific question

only concerned cross-modal transfer of shape from touch to vision and not from vision to touch.

The development of cross-modal transfer ability can be studied in two groups of subjects. The first is normal infants to learn about the developmental process. The second is patients who have forms of treatable congenital blindness such as congenital cataracts, extreme refractive error, and corneal opacities. Infant studies highlight the developmental processes that can be compared to the development of vision in subjects recovering from congenital blindness. Cross-modal transfer is assessed by familiarization with a test stimulus in one sensory modality and then recognizing the test stimulus in another modality. The primary objective in the present study is to determine whether subjects with recently removed severe bilateral congenital cataracts can transfer information about the shape of objects from the sense of touch to the newly functioning visual modality.

The present study can be compared to normal infant studies of cross-modal abilities. Cross-modal transfer is an important cognitive ability that is detectable in infancy (Rose, Feldman, Futterweit and Jankowski, 1998). One month old infants were not able to transfer information about the shapes of smooth and nubby objects between touch and vision (Maurer, Stager, and Mondloch, 1999). Streri and Molina (1993) showed that after visual habituation to a novel and familiar object, 2-month-old infants held the tactually familiar object for a longer time than a novel object. This provided evidence for visual to tactual transfer in 2-month-old infants.

Many studies have attempted to identify the mechanisms that underlie cross-modal transfer. Two types of mechanisms have been proposed. In the executive controlled model, the person recognizes a stimulus in one sense and then scans through previously established constructs to recognize it in another sense modality. This allows for broad generalizability but limits the immediacy of the sense of shared stimulus properties. In a joined image model the sensory input from the various aspects of a stimulus (sight, sound, surface texture, overall shape, heft, smell, taste) share the same template or neural circuitry. When the stimulus is sensed in one modality, the characteristics of the stimulus in other modalities are felt or at least immediately recognized. This modal requires a huge number of overlapping circuits and complex circuitry to allow one joined multisensory image of an object to generalize to other similar objects and eventually a huge number of circuits to encompass the sensory universe. It should be noted that these mechanisms may be the same as those used for many other cognitive tasks from basic memory to social decision making. And there are intermediate models such as the nexus model which combines a partial overlap of inputs followed by a search for the best outcome (Carter and Huettel, 2013).

Bushnell and Baxt (1999) adopted the executive search model to explain cross-modal recognition with familiar and unfamiliar objects in normal five-year-old children. They found that tactile to visual recognition with unfamiliar objects was poorer than with familiar objects. They theorized that newly formed memory representations of unfamiliar objects from tactile exploration may not be strong enough to support visual recognition. Recognition with familiar objects involves the activation of long-term memory and this may serve as a stronger basis for later recognition. A patient may fail to visually recognize the object if

tactile exploration encodes a property for which there is no information available for the visual system. Bushnell and Baxt theorize that this failure cannot be attributed to tactile or visual skills but rather it is the failure of the tactile and the visual system to interact. Of course, children who have just had dense congenital cataracts removed there is no information available for the visual system.

An early case study of a patient who gained sight later in life showed that he was able to recognize by vision upper case letters which he had learned earlier in life by touch. He was unable to recognize by vision the lower case letters which he had not learned by touch. This was the first documented report of a patient who demonstrated strong evidence for touch to vision transfer after an extended period of congenital blindness (Gregory and Wallace, 1963). It is also consistent with Bushnell and Baxt's (1999) hypothesis that predicts that transfer is strengthened for familiar objects using long term memory compared to novel objects.

Held uses the opposite approach to the problem. He proposed that 'capture' is a process in which perceptions of vision and touch are reunited in experimentally produced separations. Capture is the basis for adaptation to the myriad sensory rearrangements that occur in life. A well-known intermodal capture is the visual capture of auditory information in ventriloquism. Tactile and visual sensorineural channels are independent during early processing levels. Coupling between the tactile and visual signals must occur for cross-modal transfer to occur during later processing levels. In a blind patient there is no visual representation and the visual-tactile interactions can only happen after a blind person regains sight. The process called capture maps common loci for objects detected by touch and vision.

Held's study demonstrated that newly sighted patients from underdeveloped villages in India who had their congenital cataracts removed showed little transfer from touch to vision immediately after sight onset. However, the link between touch and vision was acquired within a few weeks (Held, 2009).

A few studies have tried to identify the areas of the brain that are responsible for tactile to visual integration. Hadjikhani et al (1998) used Positron Emission Tomography to identify neuronal populations involved in tactile to visual cross-modal transfer of shape. This study showed the involvement of insula-claustrum areas in cross-modal transfer when tested with eight young males. The claustrum is connected with all of the cerebral cortex and gives rise to multimodal cortical projections. It responds especially well to emotional laden information. The claustrum has been identified as an area involved in frontal lobe executive function as well as multimodal conjoining of sensory inputs. Thus, knowing the site (if this is the site) of intermodal transfer does not clarify the nature of the process at this time.

We do not know the mechanisms underlying sensory neuroplasticity in general or for touch to vision inter-modal transfer specifically. But we do know that congenitally blind people given sight through cataract surgery can recover significant visual abilities. This is seen, for example, in a case study of a 29 year-old patient whose sight was restored and functional vision was regained (Mandavilli, 2006). The author suggests that this patient's recovery was due to the visual cortex being able to regain function. In relation to touch to vision transfer, a summary of three previously reported patients in India whose blindness has been treated with cataract surgery indicates an interesting trend. The newly sighted patients

show little transfer from touch to vision immediately after sight restoration. However, this ability is acquired over time demonstrating that congenital blindness does not erase the rudimentary visual skills in the brain (Ostrovsky et al., 2006). In summary, the brain retains plasticity even though the normal timeline for visual learning has been delayed for many years.

Experiments 1 and 2: Descriptions

This thesis presents two experiments studying touch to vision transfer during the week of cataract removal in congenitally blind children. Experiment 1 assesses the existence of a tactile-visual link and compares it to intramodal touch or vision object recognition. The results from Experiment 1 will be used to interpret whether the poor performance is due to poor visual to tactile recognition, poor tactile recognition, or poor visual recognition. Experiment 2 assesses the precision of the tactile to visual transfer. It is designed to *quantify* the precision of tactile to visual recognition ability by using objects of different lengths, aspect ratios and edge curvatures. How well the patients do will allow us to quantify their performance improvement from session to session and to compare it to normal control subjects.

METHODS

Hypotheses

1. Visually-based object recognition improves with cataract removal and visual experience.
    a. Tactile object recognition is excellent before and after cataract removal.

b. Visual object recognition is very poor in the congenitally blind child but improves dramatically after surgery and continues to improve with visual experience.
c. Intermodal transfer of object recognition from tactile to visual and visual to tactile improves more slowly than intramodal improvement.

Experiment 1 tests both intramodal and intermodal object recognition paradigms by assessing the percentage of errors the subjects make.

Experiment 2 tests the precision of the subjects' ability to perform tactile-to-visual intermodal transfer object recognition using both percent errors and magnitudes of the errors for three object dimensions: length, aspect ratio, and curvature ratio.

Subjects

Inclusion & Exclusion Criteria

Some forms of treatable congenital blindness include dense congenital cataracts, corneal opacities, or extreme refractive error. To fit the criteria of the present study, a patient must have dense bilateral congenital cataracts contributing to severely reduced vision. Patients who have congenital cataracts with corneal opacities were eligible. Although difficult to quantify, change of behavior such: as stumbling in the environment, not playing with other children and having difficulty reading during the initial onset of anterior segment opacities also helped with the patient selection process. According to the parent's history, the reason that children in the present study were not brought to medical attention earlier in their life is due to lack of parental education and financial resources.

Children whose congenital blindness could not be corrected were not included in the study. Children with poor systemic health were excluded due to the risk that surgery might imperil the health of the patient.

Patients: **Experiment 1**

The three patients who participated in Experiment 1 are described below.

Deepana is a 15 year old female in the 8th grade with congenital cataracts and congenital adherent leukoma in both eyes. She also had nystagmus. Her vision was light perception in the right and left eyes upon initial evaluation at Shroff's Eye Hospital in 2008. She had penetrating keratoplasty (graft rejection) in her right eye after cataract surgery in March 2008. During the time of the study, she still had cataracts and adherent leukoma in her left eye and had not been operated on because of possible graft rejection. Cataract extraction may not have yielded functional vision due to the extreme density of the adherent leukoma in the left eye. At the time of the cross modal testing at Shroff's Eye Hospital, the patient was monocular after cataract surgery with adherent leukoma in the right eye and a cataract with adherent leukoma in the left eye. The visual acuity in the right eye after cataract surgery is counting fingers close to her face.

Vikram is a 15-year-old male with congenital cataracts in both eyes and congenital adherent leukoma which is worse in the left eye than the right eye. He also had nystagmus. His vision was light perception in the right and left eyes upon initial evaluation at Shroff's Eye Hospital. Cataract surgery was performed on July 21st 2009 in the right eye after a failed surgical attempt at another hospital in 2008 possibly due to corneal complications. The visual acuity after cataract surgery in the right eye in 2009 was counting fingers at 120 cm. At the

time of the cross modal testing at Shroff's Eye Hospital, the patient was monocular after cataract surgery with adherent leukoma in the right eye and cataracts with adherent leukoma in the left eye.

Waseema is a 14 year old female patient who presents with bilateral congenital cataracts. Waseema came to the Prakash Eye Camp before she was referred to Shroff's Eye Hospital. Her vision was light perception in the right and left eyes upon initial evaluation at the Prakash Eye Camp and Shroff's Eye Hospital. She also had nystagmus. Waseema had cataract surgery in the left eye on Monday, June 15th 2009 and cataract surgery in right eye on Thursday, June 18th 2009. Her final visual acuity in each eye after surgery was counting fingers at 160 cm in the right eye & 180 cm in the left eye.

Patients: **Experiment 2**

The three patients and four control subjects who participated in Experiment 2 are described below.

Rustom is an 8 year old male who presented with bilateral congenital cataracts. His visual acuity at distance was perception of light with the right and left eyes. In addition he presented with left esotropia (LET) of approximately 20 prism diopters and nystagmus. Cataract surgery was performed in both eyes just before testing began for the present study. The final visual acuity in each eye after surgery was counting fingers at 100 cm in the right eye & 120 cm in the left eye.

Rahul is a 10 year old male who presented with bilateral congenital cataracts. His visual acuity at distance is perception of light for the right and left eyes. In addition, he has a left esotropia (LET) of approximately 35 prism diopters and nystagmus. Cataract surgery was

performed in the left eye just before testing began for the present study however cataract surgery on the right eye was performed one month before testing began for the present study. Therefore Rahul had approximately one month of monocular visual experience prior to testing. The final visual acuity in the right eye after surgery was counting fingers at 80 cm. and 50 cm in the left eye.

Faisal is a 14 year old male who presented with bilateral cataracts. His visual acuity at distance was perception of light with the right and left eyes. He had nystagmus. Cataract surgery was performed in the left eye just before testing began for the present study however cataract surgery on the right eye was performed one month before testing began for the present study. Therefore Faisal had approximately one month of monocular visual experience prior to testing. The final visual acuity in the right eye after surgery was counting fingers at 110 cm and 80 cm in the left eye.

Four normal control subjects participated in this study. They were between the ages of 8 to 12 years old. Distance visual acuity for the normal subjects was 20/20 and their ocular history was normal.

PROCEDURES

The following experiments were performed in a well-lit room. The patient was seated comfortably in front of a table.

Experiment 1

The intramodal and cross-modal tests were performed post-operatively on the three patients described above. Two different sets of objects were used to assess object recognition and its

cross-modal transfer using four procedures: tactile-to-tactile, visual-to-visual, tactile-to-visual, and visual-to-tactile. In the Lego study the subject must differentiate between 15 Lego objects of very different sizes and shapes (figure 1). In the Curvature study the subject must differentiate among an array of 5 barrel shaped and 5 pincushion shaped flat objects that also had different sizes (figure 2). Thus, the array had a total of 10 objects.

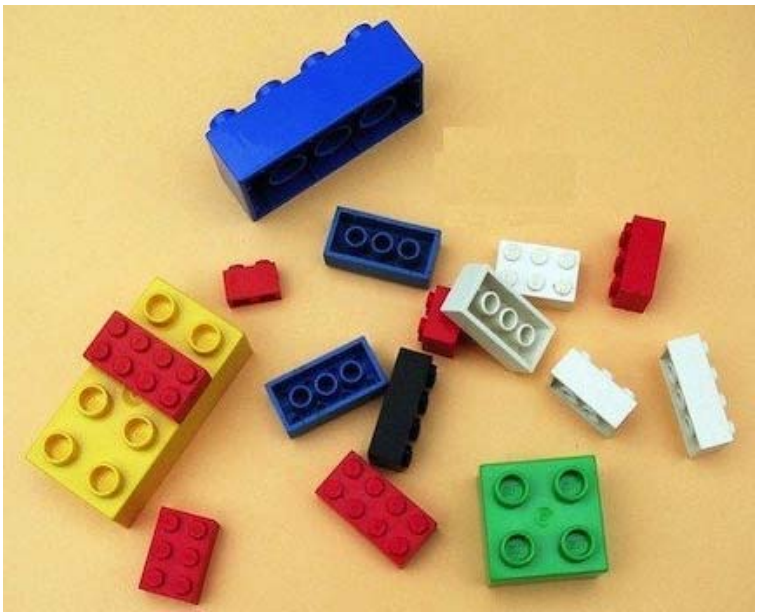
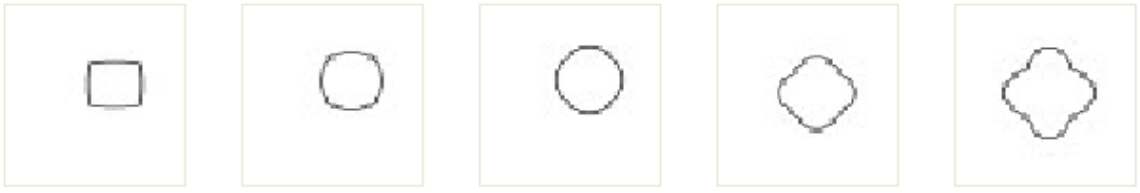


Figure 1. A typical array of the Lego objects as they were presented to the subjects.



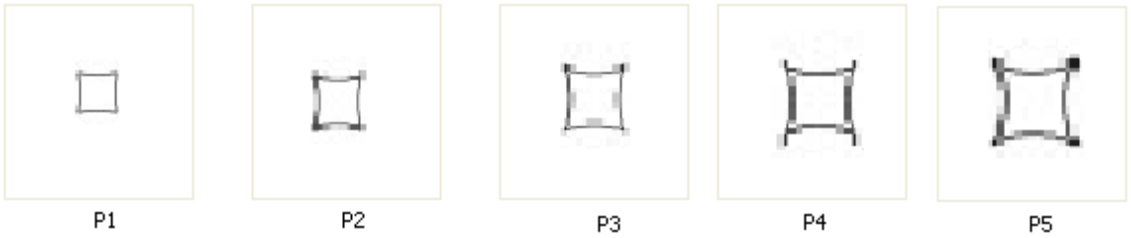


Figure 2. Representation of the curvature objects showing their relative sizes and shapes. They were presented to the subjects in a scattered array similar to the presentation of the Lego objects.

1. In the tactile-tactile condition, the patient was blindfolded. Fifteen Lego objects or 10 curvature objects were placed on a board in front of where the subject was seated. The patients examined by touch one of the randomly selected Lego objects that the experimenter placed in his/her hand. The subject had 10 seconds to examine each object by touch. The object was then placed back on the board with the other objects. The patient then had to choose by touch which object he/she had just examined by touch.

2. In the tactile-visual task, the patient was blindfolded when he/she was given a shape to examine first by touch. The subject had 10 seconds to examine each object by touch. The object was then placed back with the other objects. The blindfold was removed and the patient had to visually choose which object he/she had just examined by touch.

3. In the visual-tactile condition the patient had to visually examine each object for 10 seconds. The experimenter took back the object and blindfolded the subject. The object was then placed back on the board with the other objects. The subject then had to examine the objects by touch and select the object he/she had examined visually.

4. In the visual-visual condition the subject had to visually examine an object for 10 seconds. The experimenter replaced the object back on the board while the subject was

momentarily blindfolded. When the blindfold was removed, the patient had to visually select the object they had just examined visually.

The testing of the four conditions was always presented in the same order as in 1 through 4 above. Lego testing preceded Curvature testing. Each object in an array was used as the sample object in each condition. Thus, there were 15 trials for each Lego test and 10 trials for each Curvature test. The number of correct responses was divided by the total number of objects and multiplied by 100 to calculate the percentage of correct responses. Table 1 shows correct percentages in the cross modal task for four conditions: tactile-tactile, tactile-visual, visual-tactile, and visual-visual for each patient pre and post-operatively.

Experiment 2

The perception of shape can be assessed in more detail by measuring the error incurred in matching objects of different lengths, aspect ratios and curvatures. In Experiment 2, the perception and visual-to-tactile intermodal transfer of object shape recognition has been assessed before and after cataract surgery.

Light colored wooden objects of different lengths, aspect ratios or curvatures were presented on a dark board. The patient was asked to close his/her eyes. One object was handed to the patient on each trial in a pre-determined random order. First the patient was told to carefully examine the object by touch and to remember its characteristics. The patient

was given 10 seconds to examine the object by touch. The object was then placed back on the board with the other objects. Then, without touching the object, the patient was asked to visually identify the object among the many others by pointing to it.

Part I: Length

The patient was blindfolded and examined a small wooden stick of a specific length by touch. The object was then placed back on the board with the other objects. The patient was then shown the array of 23 sticks of different lengths. The patient had to visually choose the stick that most closely matched the length of the stick that he/she had touched. The patient was not allowed to touch the object sticks while trying to identify the stick of the specified length.

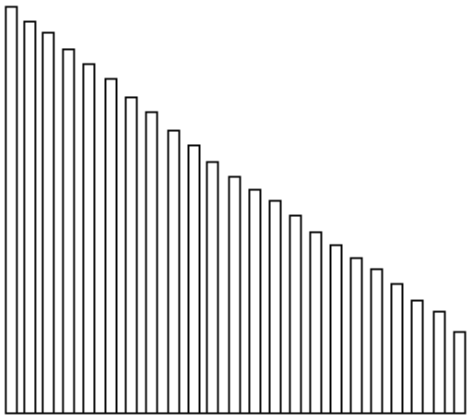


Figure 3A. Representation of sticks showing their relative lengths.

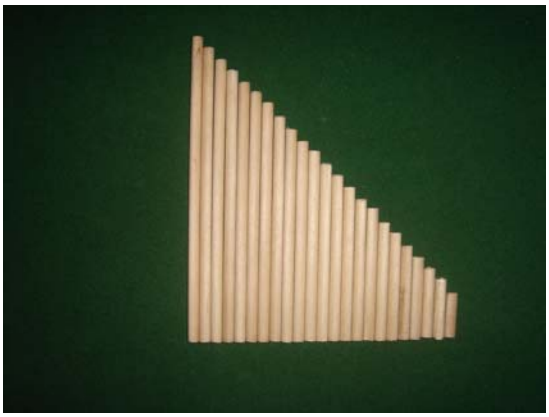


Figure 3B. Sticks as presented to the patients.

Part 2: Aspect Ratio

Rectangles can look almost like squares if the length of one side is almost the same as the other side. If one side is much longer than the other side a rectangle can look like the sticks presented in part 1. We can define the shape of a rectangle by its aspect ratio which is the ratio of the long side of the rectangle to the small side of the rectangle. In this experiment aspect ratio is the main experimental variable. In addition, the rectangles come in 3 sizes. The small sizes were between 1 to 1.5 cm, medium sizes were between 1.5-2.0 cm, and large sizes were between 2.0-2.5 cm. Figure 4A below shows the array of shapes and sizes of the rectangles in this experiment. Objects R1-R6 are the small-sized rectangles of different aspect ratios, R7-R12 show the medium-sized aspect ratios, and R13-18 show the large-sized aspect ratios. The patient was blindfolded and an object with a specific aspect ratio was examined by touch by the patient. The object was then placed back on the board with the other objects. The patients had to visually choose the object that most closely matched the size and aspect ratio of the object they had touched. The patient was not allowed to touch the objects while trying to visually identify the specified object.

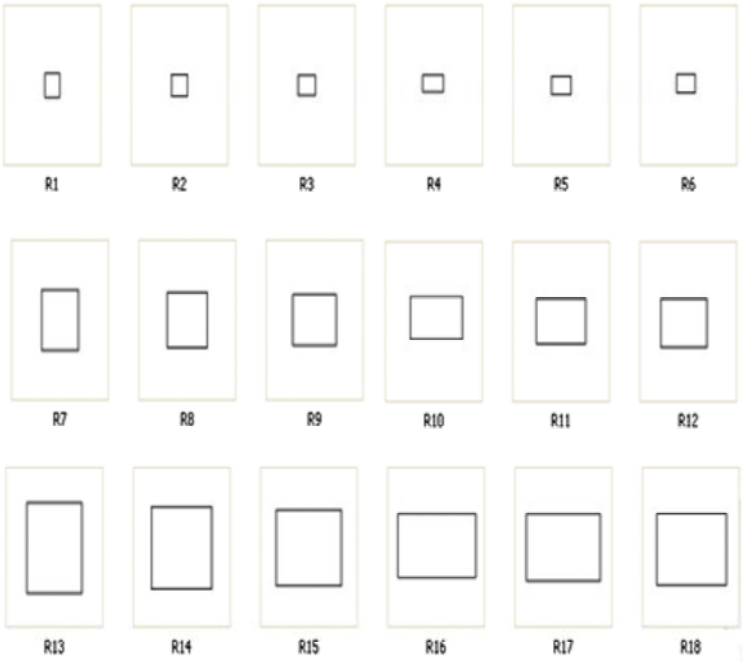


Figure 4A. Representation of 18 rectangles showing their different aspect ratios and sizes.

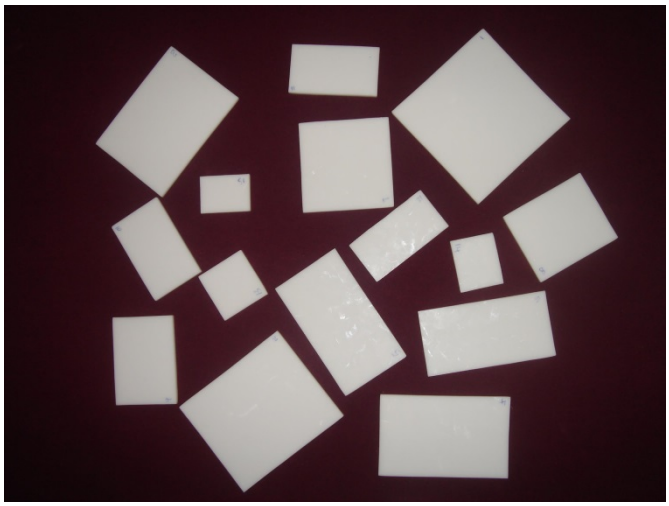


Figure 4B. The array of rectangles as they were presented to the subjects. Note that one of the objects was not available for the photo shoot.

Part 3: Curvature

The curvature experiment is based on distorting the sides of a series of squares. The experiment consisted of 15 pincushion shaped objects, squares with their sides curved inward, and 15 barrel shaped objects, squares with their sides bulging outward. There were 3 different sizes (small, medium, and large) for each of the pincushion and barrel objects. B1-B5 and P1-P5 represent small-sized, B5-B10 and P5-P10 represent medium-sized and B10-B15 and P10-P15 represent large-sized objects. The curvature of an object relative to its size, the curvature ratio, was calculated by measuring the distance from the middle of the side to the middle of the opposite side of the square in both directions and then measuring the

distance between opposite corners of the square. The cross-corner distance is divided by the cross-side distance to calculate each curvature ratio.

A total of 30 white objects were laid down on a surface of dark solid cardboard. The patient was blindfolded and an object of a specific curvature was examined by touch by the patient. The object was then placed back on the board with the other objects. The patient was then shown the array of objects with different curvatures. The patient had to visually choose the object that closely matched the curvature of the object he/she had just touched. The patient was not allowed to touch the objects when trying to identify the specified object. In the diagram below, “B” refers to barrel shape and “P” refers to pincushion shape.

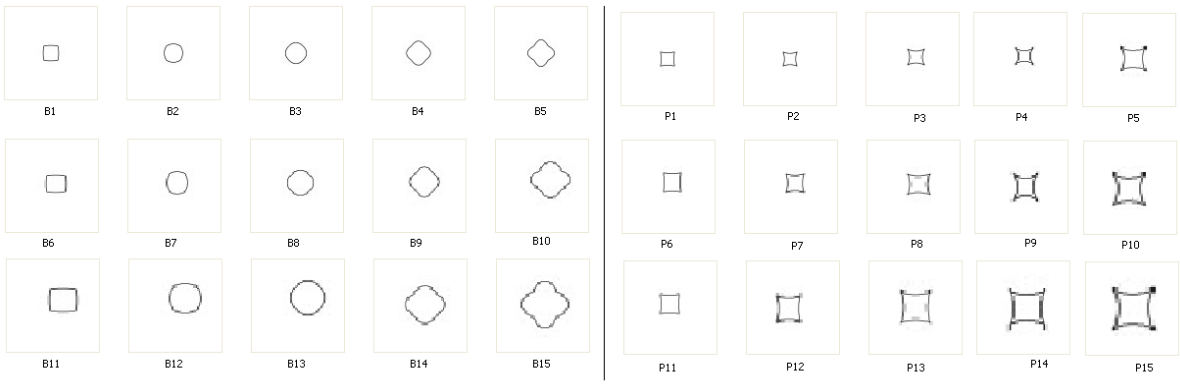


Figure 5A. Representation of curvature ratios and relative sizes of the 30 squares with barrel and pincushion distortion of their sides.



Figure 5B. The array of 30 squares with different side curvatures and sizes as they were presented to the subjects Curvature. Note that one of the objects was not available for the photo shoot.

The length task involves a single one dimensional discrimination. The aspect ratio and curvature tests assessed the patients' ability to differentiate their two shape characteristics and the sizes of objects. It should be noted that the number of objects the subject had to choose from in the three parts of Experiment 2 varied. The length test (Part 1) had 23 objects, the aspect ratio test (Part 2) had 18 objects and the curvature test (Part 3) and 30 objects (15 barrels and 15 pincushions).

In the results for Experiment 2, the first set of graphs show the overall error percent incurred in the experiments. The second set of graphs highlight the sizes of the errors the patients made in when recognizing length, aspect ratio and curvature ratios.

Visual Acuity Measurement

Visual acuity was measured before cataract surgery by assessing the presence of light perception with a pen light at 1.0 meter, hand motion at 1.0 meter in different parts of the

visual field and monocular Finger Counting Visual Acuity in the right and left eyes. Post operatively, visual acuity was recorded as the distance at which patients could accurately perform the Finger Counting Test. One, two or four fingers were shown at pre-determined distances. The patients had to accurately state the number of fingers the examiner was holding up and perform this test for 10 trails.

Visual acuity was measured pre-operatively and post-operatively for all patients. In addition, Waseema's visual acuity was measured over time as she was at the Shroff's Hospital for a longer duration compared to the other patients.

RESULTS

Experiment 1

Table 1 shows the percentages correct in the four conditions of the cross modal task pre-operatively and post-operatively. Deepana and Vikram had cataract surgery performed on only one eye due to corneal disease in both eyes. Waseema had cataract surgery on both eyes.

The table below presents the data twice. The first number represents the percentage correct. It is the number of correct responses divided by the total number of trials.
The second number represents the percentage corrected for chance. The following formula was used to calculate this number: $xc = (x - c) / (100 - c)$ where 'xc' represents the percentage corrected for chance, 'x' represents the percentage correct, and 'c' represents the number of objects. There were 15 Lego objects and 10 Curvature objects.

The graphs below represent the percentage correct in the cross modal and intramodal tasks for the Lego and the Curvature tests for each of the patients.

Table 1: Percent correct responses in four test conditions as a function of time. The first number represents the percentage correct. The second number represents the percentage corrected for chance. Note that three of the corrected numbers are negative.

Deepana								
Lego	*Tactile-Tactile*		*Tactile-Visual*		*Visual-Tactile*		*Visual-Visual*	
Pre-Op	87%,	85%	20%,	6%	20%,	6%	0%,	-18%
Post Op Day 1	87%,	85%	53%,	45%	60%,	53%	20%,	6%
Post Op Day 3	87%,	85%	60%,	53%	60%,	53%	27%,	14%
Post Op Day 5	87%,	85%	67%,	61%	73%,	68%	40%,	29%
Post Op Day 7	87%,	85%	67%,	61%	73%,	68%	60%,	53%
Curvature								
Pre-Op	75%,	72%	25%,	17%	25%,	17%	8%,	2%
Post Op Day 1	75%,	72%	67%,	63%	75%,	72%	100%,	100%
Post Op Day 3	75%,	72%	67%,	63%	75%,	72%	92%,	91%
Post Op Day 5	75%,	72%	75%,	72%	83%,	81%	100%,	100%
Post Op Day 7	75%,	72%	75%,	72%	100%,	100%	100%,	100%

Vikram								
Lego	*Tactile-Tactile*		*Tactile-Visual*		*Visual-Tactile*		*Visual-Visual*	
Pre-Op	100%,	100%	20%,	6%	20%,	6%	20%,	6%
Post Op Day 1	100%,	100%	87%,	85%	100%,	100%	73%,	68%
Post Op Day 3	93%,	92%	73%,	68%	93%,	92%	73%,	68%
Post Op Day 5	100%,	100%	80%,	76%	100%,	100%	80%,	76%
Post Op Day 7	100%,	100%	87%,	85%	100%,	100%	93%,	92%
Curvature								
Pre-Op	75%,	72%	25%,	17%	33%,	26%	17%,	8%
Post Op Day 1	75%,	72%	42%,	36%	50%,	44%	42%,	36%
Post Op Day 3	83%,	81%	50%,	44%	58%,	53%	42%,	36%
Post Op Day 5	83%,	81%	67%,	63%	83%,	81%	75%,	72%
Post Op Day 7	83%,	81%	75%,	72%	83%,	81%	83%,	81%

Waseema								
Lego	*Tactile-Tactile*		*Tactile-Visual*		*Visual-Tactile*		*Visual-Visual*	
Pre-Op	100%,	100%	13%,	2%	20%,	6%	7%,	-9%
Post Op Day 1	73%,	68%	67%,	61%	33%,	21%	60%,	53%
Post Op Day 3	73%,	68%	67%,	61%	47%,	38%	67%,	61%
Post Op Day 5	80%,	76%	80%,	76%	53%,	45%	67%,	61%

Post Op Day 7	80%,	76%	87%,	85%	73%,	68%	87%,	85%
Curvature								
Pre-Op	100%,	100%	17%,	8%	0%,	-18%	17%,	8%
Post Op Day 1	58%,	53%	50%,	44%	25%,	17%	58%,	53%
Post Op Day 3	67%,	63%	58%,	53%	33%,	26%	58%,	53%
Post Op Day 5	75%,	72%	75%,	72%	58%,	53%	75%,	72%
Post Op Day 7	100%,	100%	75%,	72%	67%,	63%	75%,	72%

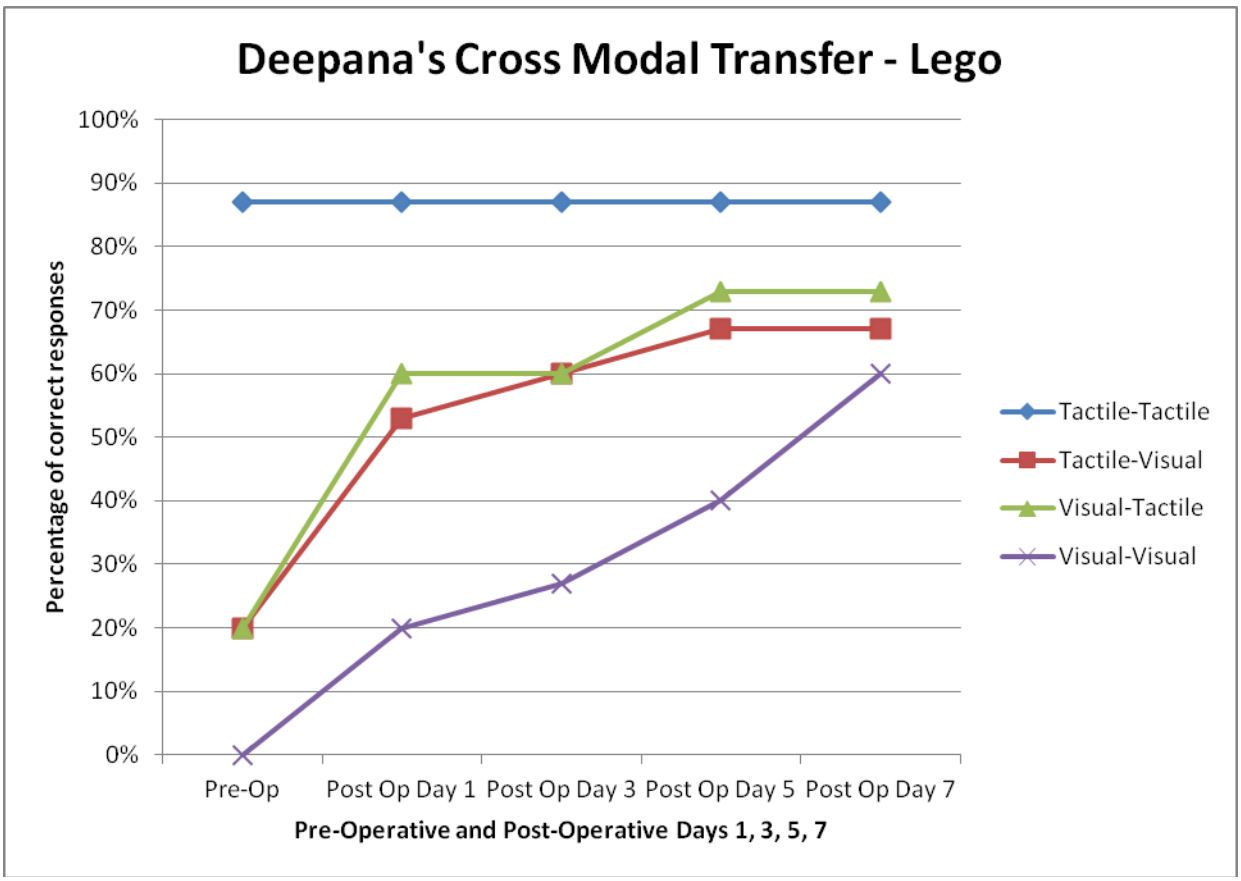


Figure 6. Percent correct responses in the four test conditions as a function of days since surgery. Note the slow improvement over time.

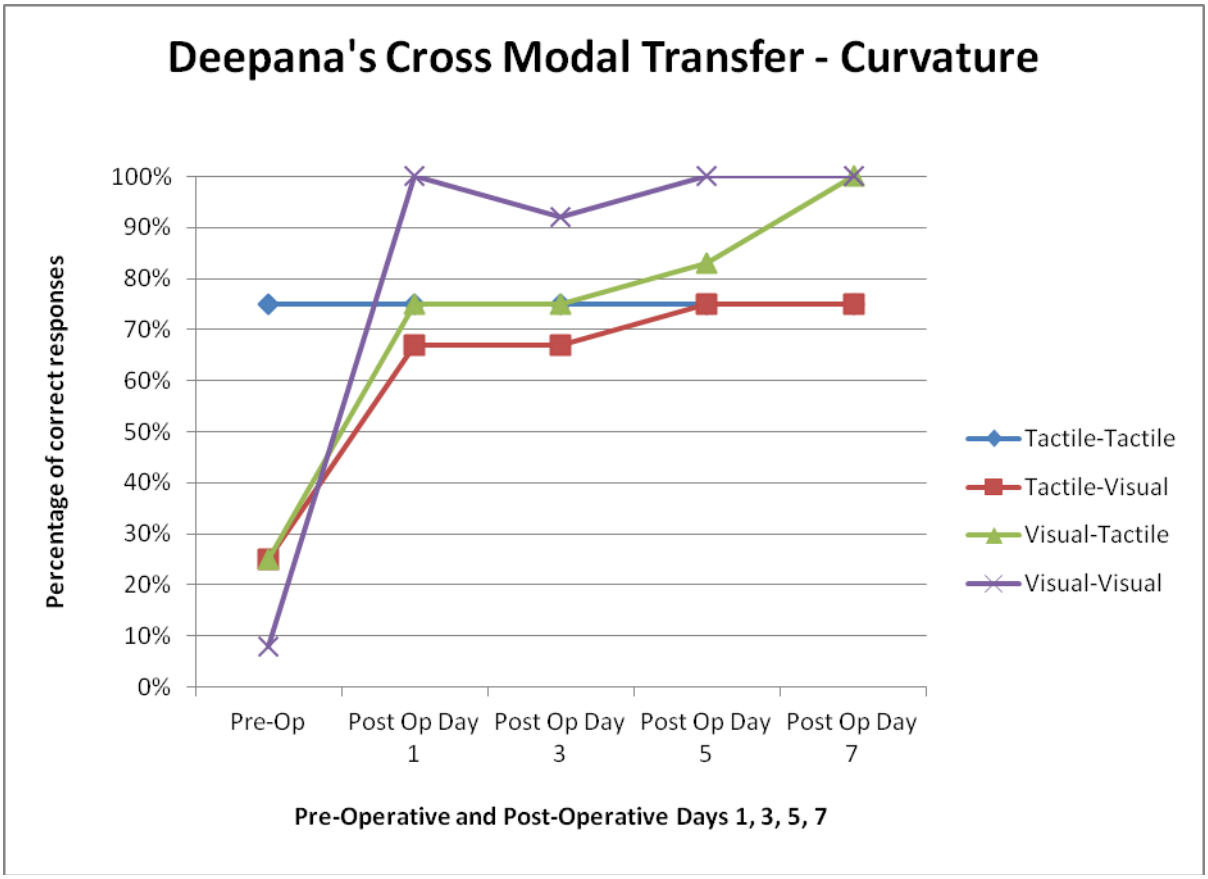


Figure 7. Percent correct responses in the four test conditions as a function of days since surgery. Note the initial strong improvement followed by slow improvement over time.

Deepana performed very well in the tactile-tactile condition in the Lego task. The percentage correct was above 80% for the tactile-tactile task before and after surgery. Her tactile-visual and visual-tactile skills were about 20% preoperatively and improved to better than 50% on postoperative day 1. But then both tasks improved little during the following days. On the visual-visual task performance was at 0% preoperatively and slowly improved to about 70% on the seventh day after cataract surgery.

Deepana's performance was 75% on the tactile-tactile task in the curvature experiment on every day of testing. She performed poorly on the tactile-visual and visual-

tactile tasks scoring just 25% correct preoperatively. Her percentage of correct responses improved to about 70% postoperatively on day 1 improving just slightly thereafter. In the visual-visual task she scored 0% correct preoperatively and then on the 1st post-operative day she scored 100% correct and remained at 90% to 100% on the following days.

Deepana performed similarly on the Lego and curvature tasks for tactile-tactile and the intermodal tasks but remarkably different on the visual-visual task. On the curvature visual –visual task she improved slowly after surgery improving up to a 70% correct on day 7 while on the Lego task she went from 0% preoperatively to 100% on post-operative day 1 and remained at this high performance level thereafter.

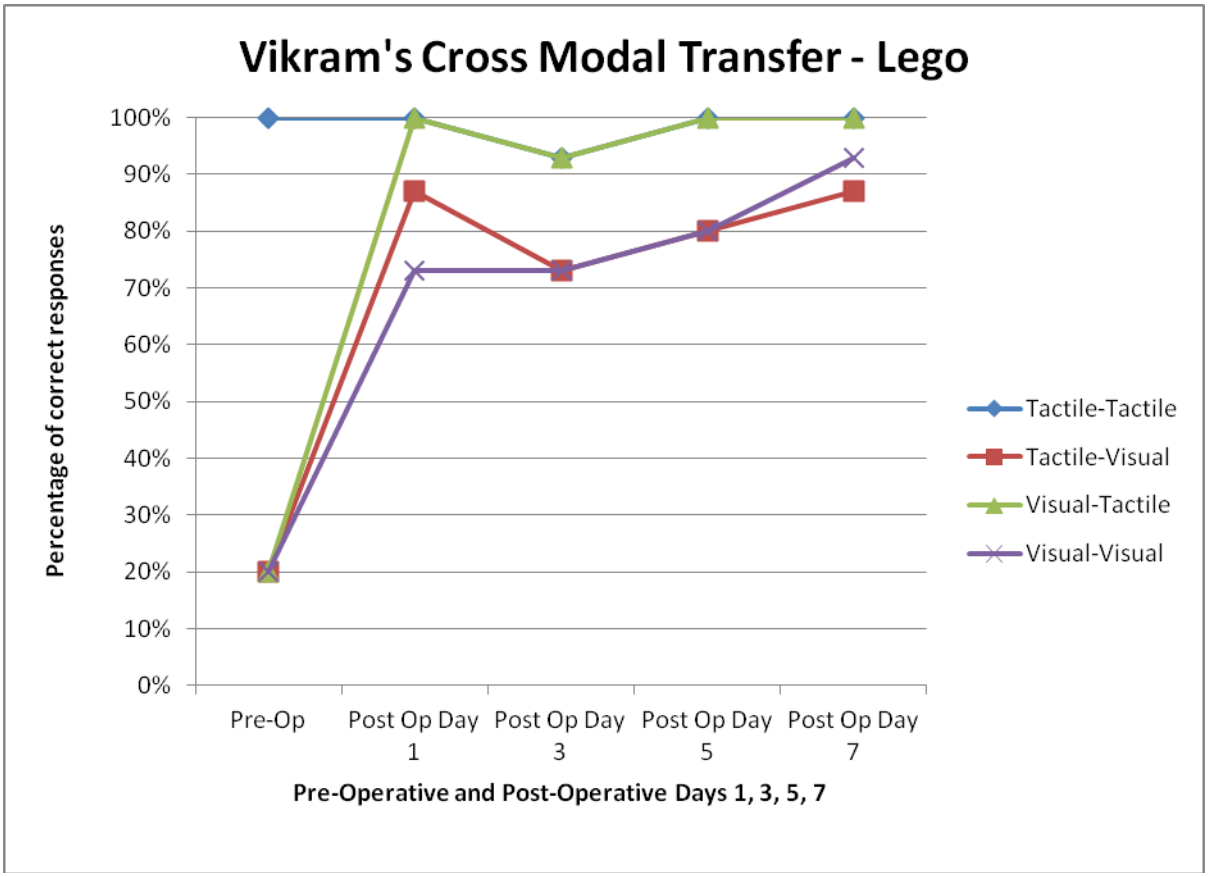


Figure 8. Percent correct responses in four test conditions as a function of days since surgery. Note the initial strong improvement followed by slow improvement over time.

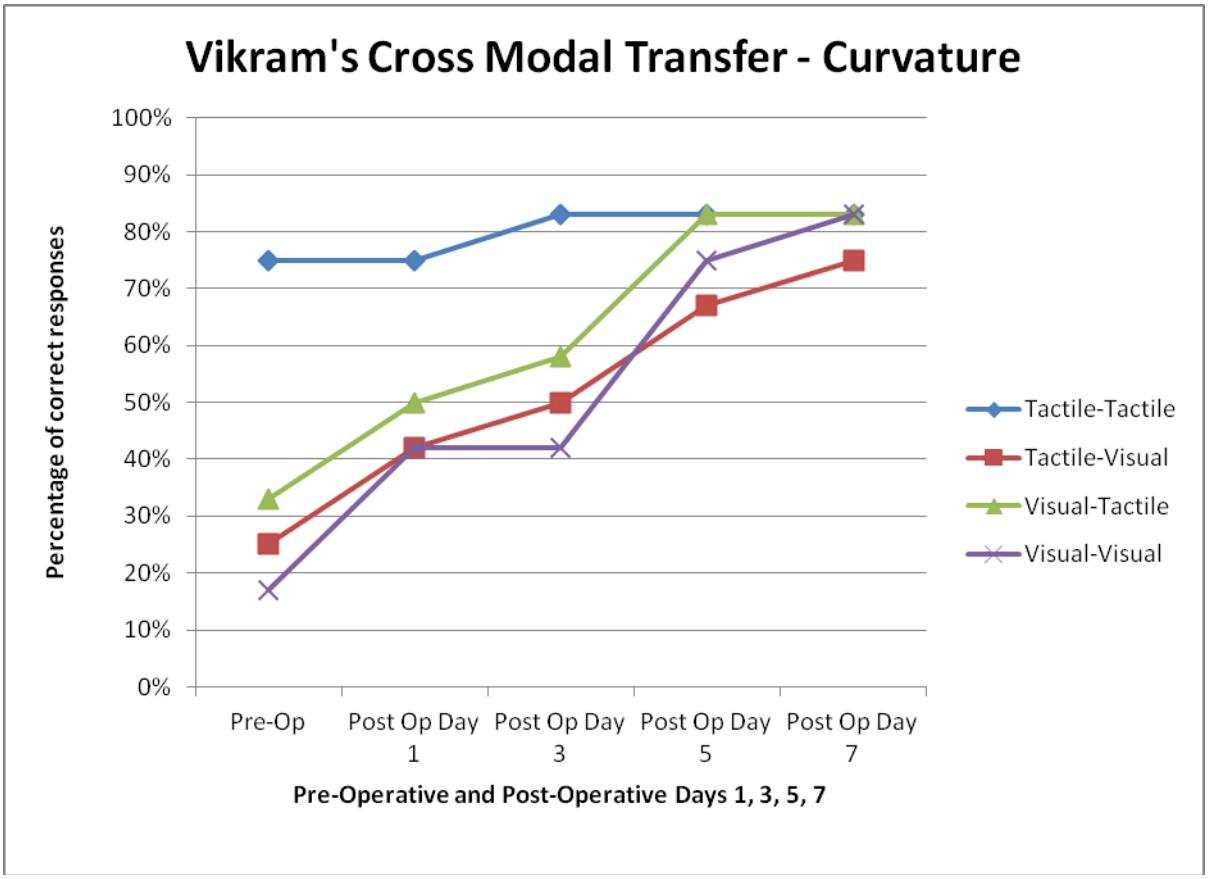


Figure 9. Percent correct responses in four test conditions as a function of days since surgery. Note the slow improvement over time.

Vikram obtained 100% in the tactile-tactile task in the Lego task pre and postoperatively. Vikram's percentage of correct responses improved to 87%, 100%, and 73% in tactile-visual, visual-tactile and visual-visual tasks respectively on postoperative day 1 and improved little after that.

In the Curvature task, Vikram's percentage correct was above 70% in the tactile-tactile transfer and remained high thereafter. The tactile-visual, visual-tactile, and visual-visual tasks slowly improved over the course of the testing period. Thus the Lego task showed an immediate post-operative improvement but no further improvement during the

next week while the curvature task showed a slow improvement during the week after surgery.

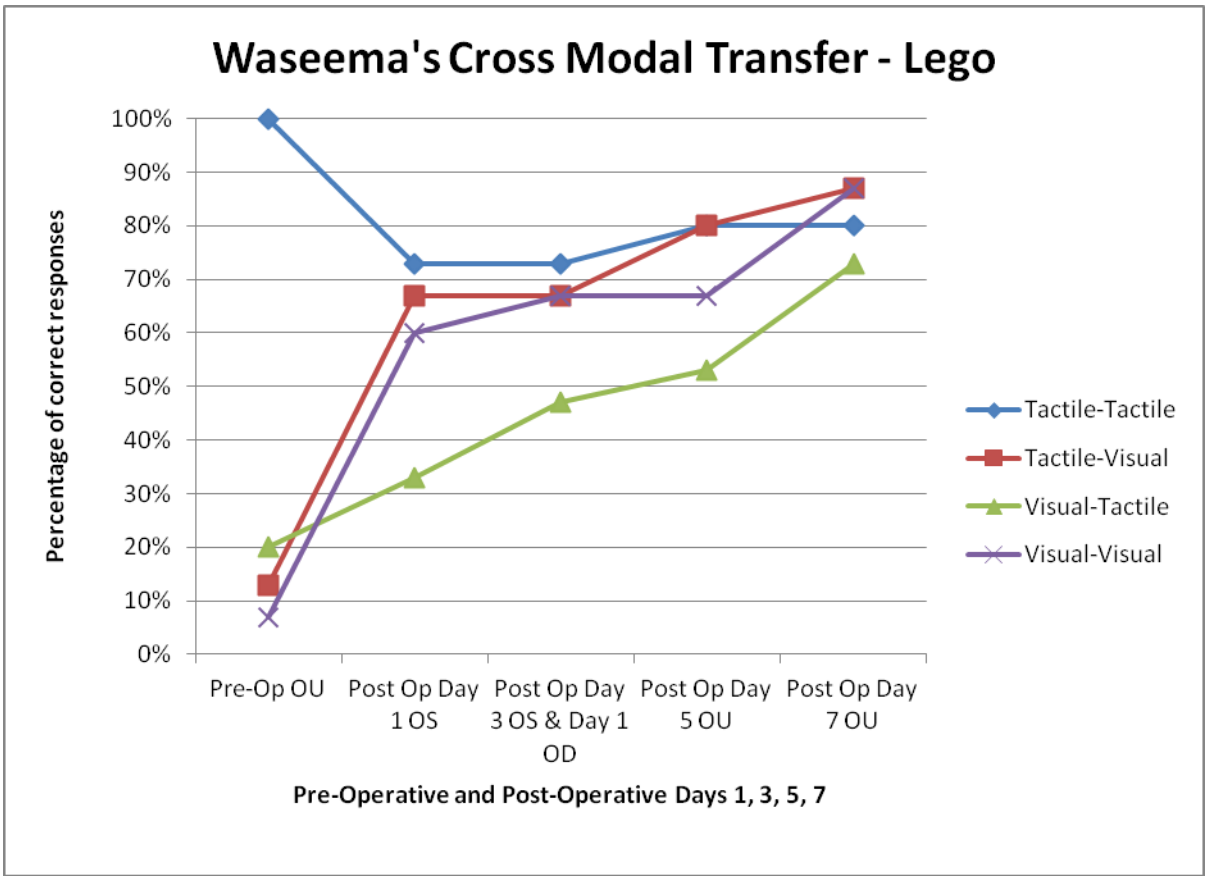


Figure 10. Percent correct responses in four test conditions as a function days since surgery. Note the initial strong improvement followed by slow improvement for two of the three visually involved tasks. Note that the visual-tactile task shows a slow improvement over time.

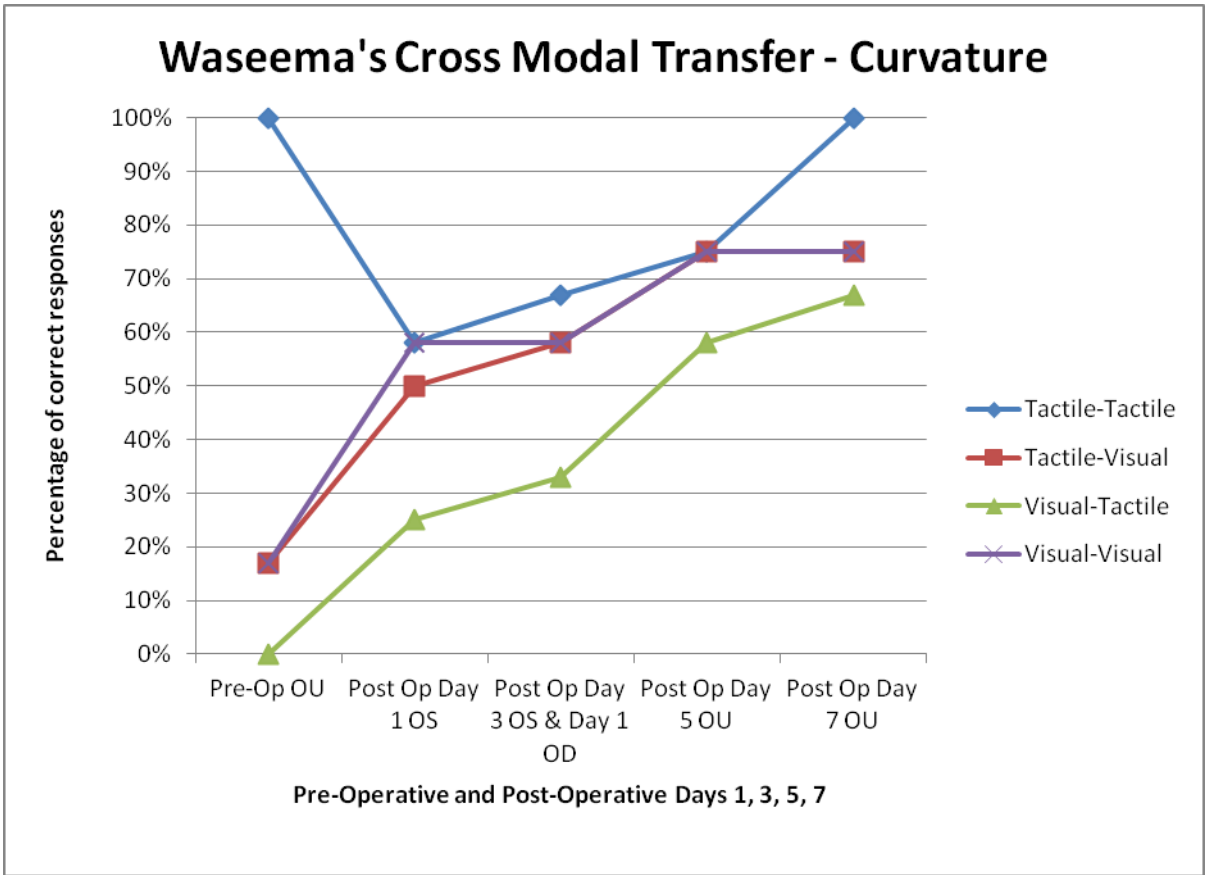


Figure 11: Percent correct responses in four test conditions as a function of days since surgery. Note the slow improvement over time.

Waseema had cataract surgery on the right eye 3 days after surgery on the left eye. Therefore pre-operative was before cataract surgery in both eyes. Post-operative day 1 was after cataract surgery in the left eye and post-operative day 3 was 3 days after the first cataract surgery while the right eye had surgery early that morning. Therefore, starting on day 3 post-operative, Waseema had visual experience in both eyes. The experiments were performed binocularly thereafter.

Waseema had 100% correct responses in the tactile-tactile preoperative condition for the Lego task but then performed slightly worse (about 80% correct) after surgery. Her

performance in the tactile-visual, visual-tactile, and visual-visual tasks were under 20% pre operatively. Waseema showed improvement to about 60% immediately after surgery on the tactile-visual and visual-visual tasks and then showed only slight improvement over the course of the 7-day testing period. Her visual-tactile performance showed slow improvement and was close to 80% on post-operative day 7. Waseema's performance on the curvature task was very similar to that on the Lego task.

Waseema was the only subject with systematic visual acuity testing (Figure 12). For the left eye there was strong improvement immediately after surgery. The right eye also improved after left eye surgery but showed a lesser improvement when the right eye itself underwent surgery.

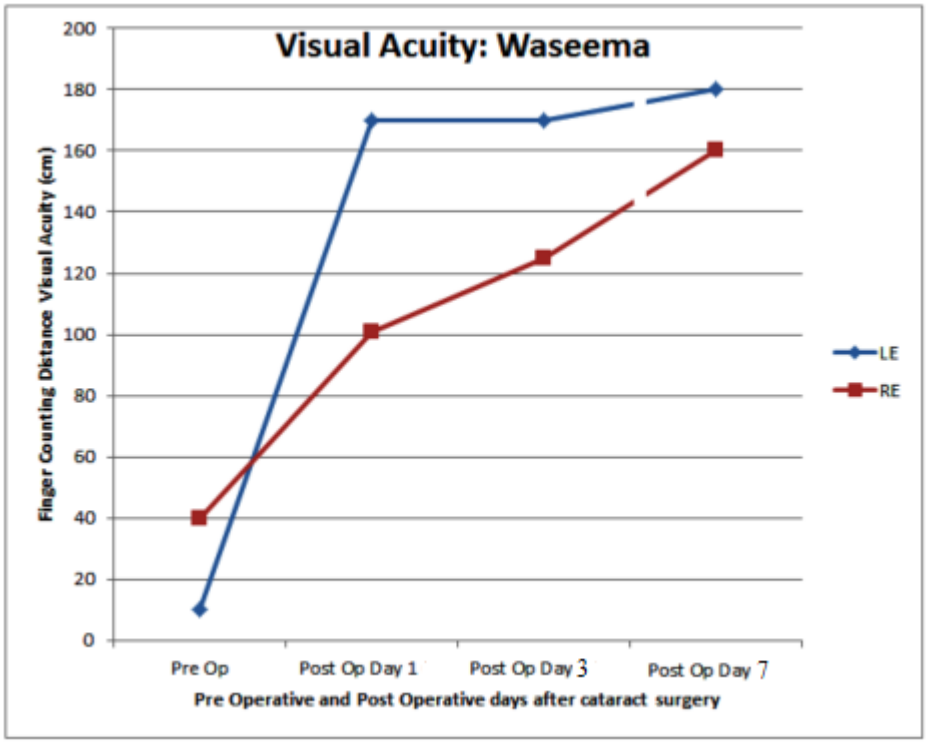


Figure 12: Distance visual acuity pre operatively and on successive days after cataract surgery in the right and left eyes. The break in the graph represents measure of visual acuity monocularly before the break in the line and binocularly after the break in the line.

Table 2: Trend analysis for each patient for four test conditions

		Tactile-Tactile	Tactile-Visual	Visual-Tactile	Visual-Visual
Deepana	Lego	0%	32%	33%	40%
	Curvature	0%	40%	40%	43%
Vikram	Lego	3%	44%	51%	37%
	Curvature	5%	27%	35%	19%
Waseema	Lego	0%	31%	20%	24%
	Curvature	0%	27%	30%	30%

Trend analysis is used in the present study to assess how patients' performance changes over time. A linear trend line is modeled in the present study by $y = mx + c$ where x and y are the variables, m is the slope and c is the 'y' intercept. Trend analysis was calculated using Excel software. Table 2 shows the trend analysis for each patient for both the Lego and Curvature tasks. The analysis shows relatively similar changes for the all three subjects and tasks. Deepana showed about a 40% improvement in the visual-visual and intermodal tasks for both the Lego and Curvature tasks. Vikram showed a greater improvement for the Lego than the curvature tests and the least improvement for the visual-visual task in both cases. Waseema showed similar changes for the visual-visual and intermodal tasks for both the Lego and Curvature tests. Cross modal transfer improved after cataract surgery in all cases. Since Waseema had cataract surgery in both eyes at the time of testing she should have shown a larger improvement than the other two children but this was not the case.

Experiment 2

The table below shows the error percentage for stick length, aspect ratio, and curvature ratio for three patients and four control subjects. Note that these are different

subjects than in experiment 1 and each control subject performed the experiment just once.

The data listed below shows just the one trial for each control patient.

Table 3: Error percentage for stick length, rectangle aspect ratio, and curvature ratio as a function of time in days after surgery. Each of the four control subject performed the experiment once.

Error Percentage for Stick Length

	Faisal	Rustom	Rahul	Controls
Pre-Op	52%	31%	31%	
Post Op Day 1	35%	28%	29%	
Post Op Day 2	32%	24%	24%	
Post Op Day 3	29%	23%	24%	
Post Op Day 4	23%	22%	19%	9%, 10%, 10%, 2%

Error Percentage for Rectangle Aspect Ratio

	Faisal	Rustom	Rahul	Controls
Pre-Op	34%	24%	22%	
Post Op Day 1	25%	22%	17%	
Post Op Day 2	25%	18%	16%	
Post Op Day 3	23%	17%	15%	
Post Op Day 4	17%	15%	13%	7%, 9%, 6%, 4%

Error Percentage for Curvature Ratio

	Faisal	Rustom	Rahul	Controls
Pre-Op	54%	38%	40%	
Post Op Day 1	43%	22%	30%	
Post Op Day 2	32%	18%	27%	
Post Op Day 3	28%	17%	26%	
Post Op Day 4	28%	15%	21%	6%, 2%, 9%, 3%

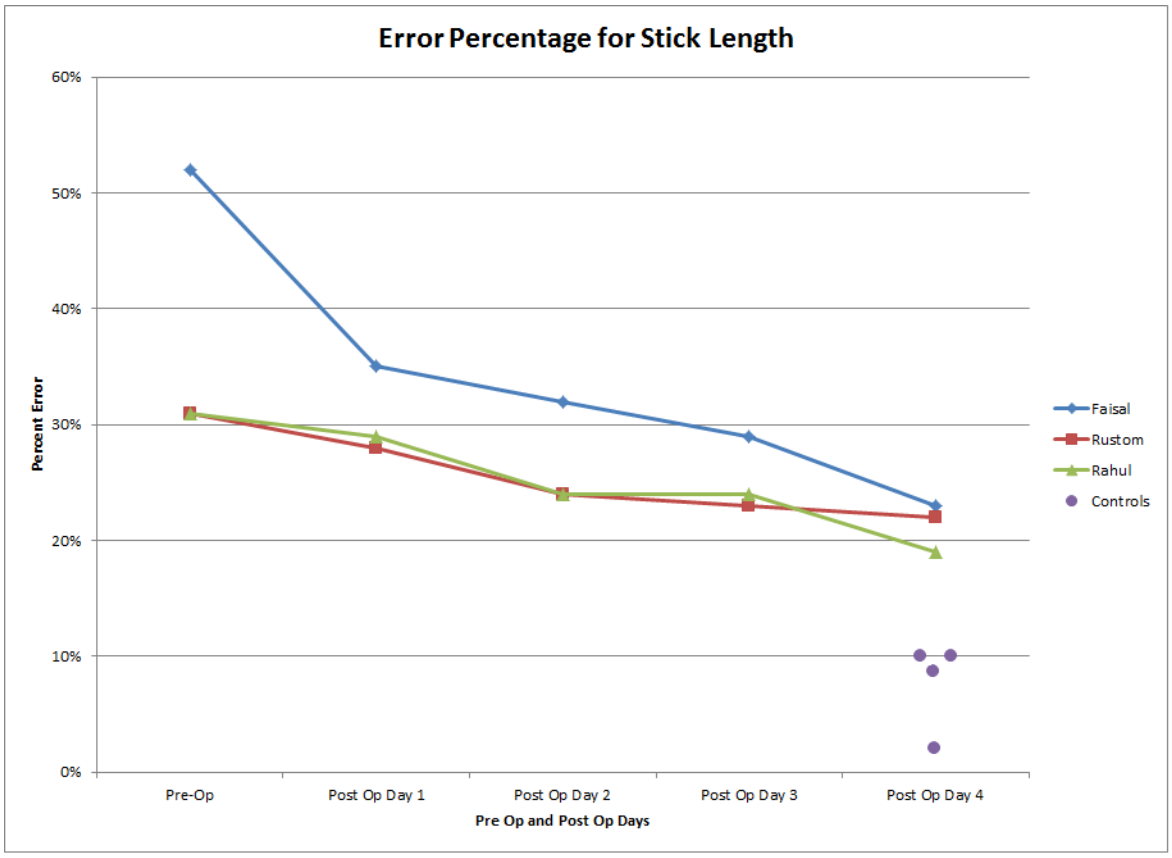


Figure 13: Error percentages for stick length judgments as a function of time in days relate to cataract replacement surgery. Note the slow improvement over time.

Figure 13 above shows error percentage in tactile-to-visual transfer of stick length pre-operatively and four days post operatively. Faisal had the largest pre-operative error percentage at 50% compared to Rustom and Rahul who had about a 30% error rate preoperatively. Faisal showed a large improvement in error percentage of about 15% between preoperatively and 1 day post operatively. Rustom and Rahul showed almost no change in error percentage (about 2-3%) between the preoperative and 1 day post-operative measurement. The three subjects continued to show an improvement of about 2-3% each day after the initial post-operative measurement. The four control subjects showed 10% or less error rates.

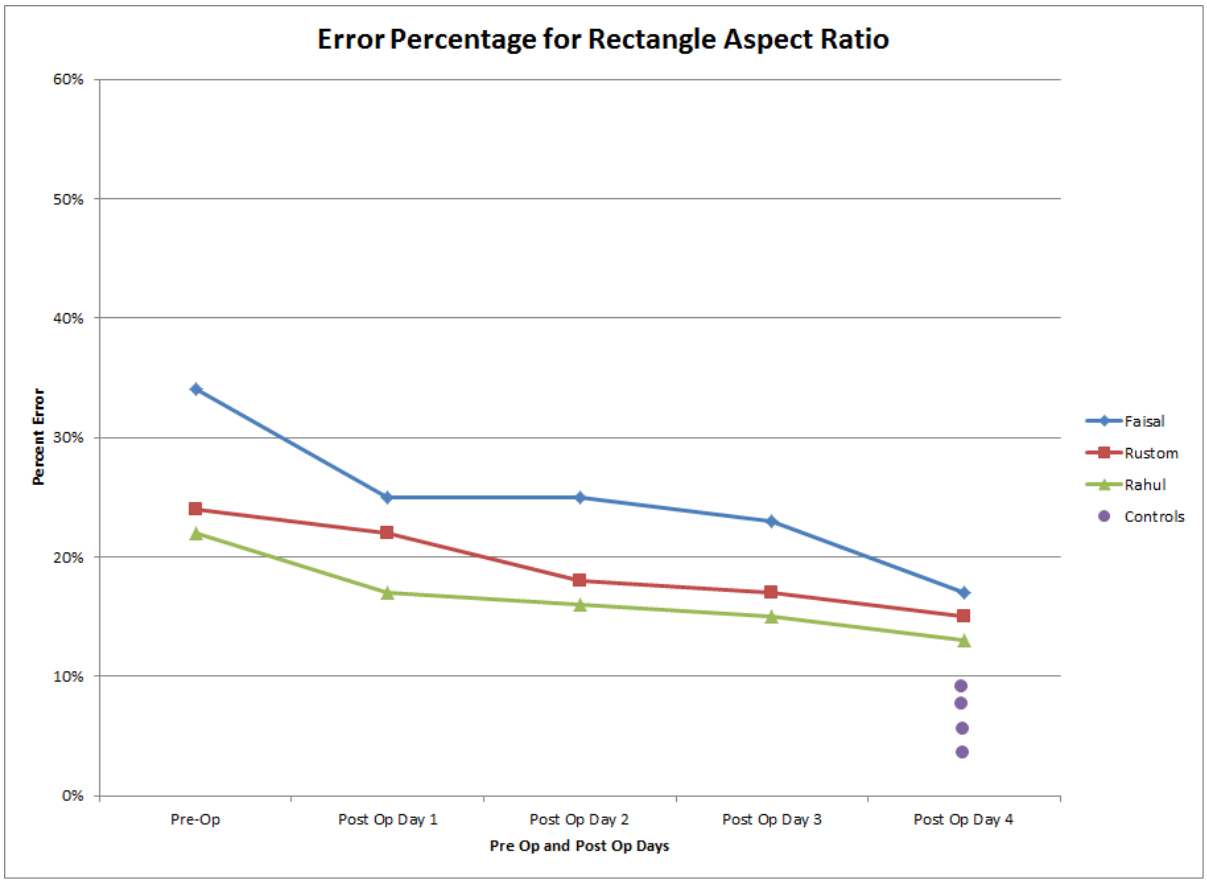


Figure 14: Error percentage for rectangle aspect ratio judgments as a function of time in days relative to cataract replacement surgery. Note the slow improvement with time.

Figure 14 shows error percentages in the tactile-visual transfer of rectangle aspect ratio judgments. Faisal showed the largest error percentage at 34% pre operatively. Rustom and Rahul showed a 22% and 24% error respectively. Post operatively, Faisal showed the largest decrease in error percentage (10%) on post-operative 1 day. Rustom and Rahul showed just a 2% and 3% error decrease, respectively. Rustom's day 1 post-operative measurement was 22% and Rahul's was 18%. Faisal, Rustom and Rahul showed a 2-3% day-by-day decrease in error percentage post-operatively. On post-operative day 4, Faisal, Rustom and Raul's error percentages were 17%, 15% and 14%, respectively. The four

control subjects showed less than a 10% error in the tactile-to-visual transfer of rectangle aspect ratio.

Although Faisal showed a worse performance preoperatively, the three patients showed a relatively similar pattern of post-operative improvement. On day 4 they had a mean error rate of 15% while the control subjects had a mean rate of just 6.5%.

The patient who had cataract surgery performed in both eyes (Rustom) just prior to testing and the two patients (Faisal and Rahul) who had one cataract removed a month earlier showed similar postoperative error rates and improvement rates.

All three patients demonstrated a small decrease in errors the day after surgery and showed slow improvement thereafter.

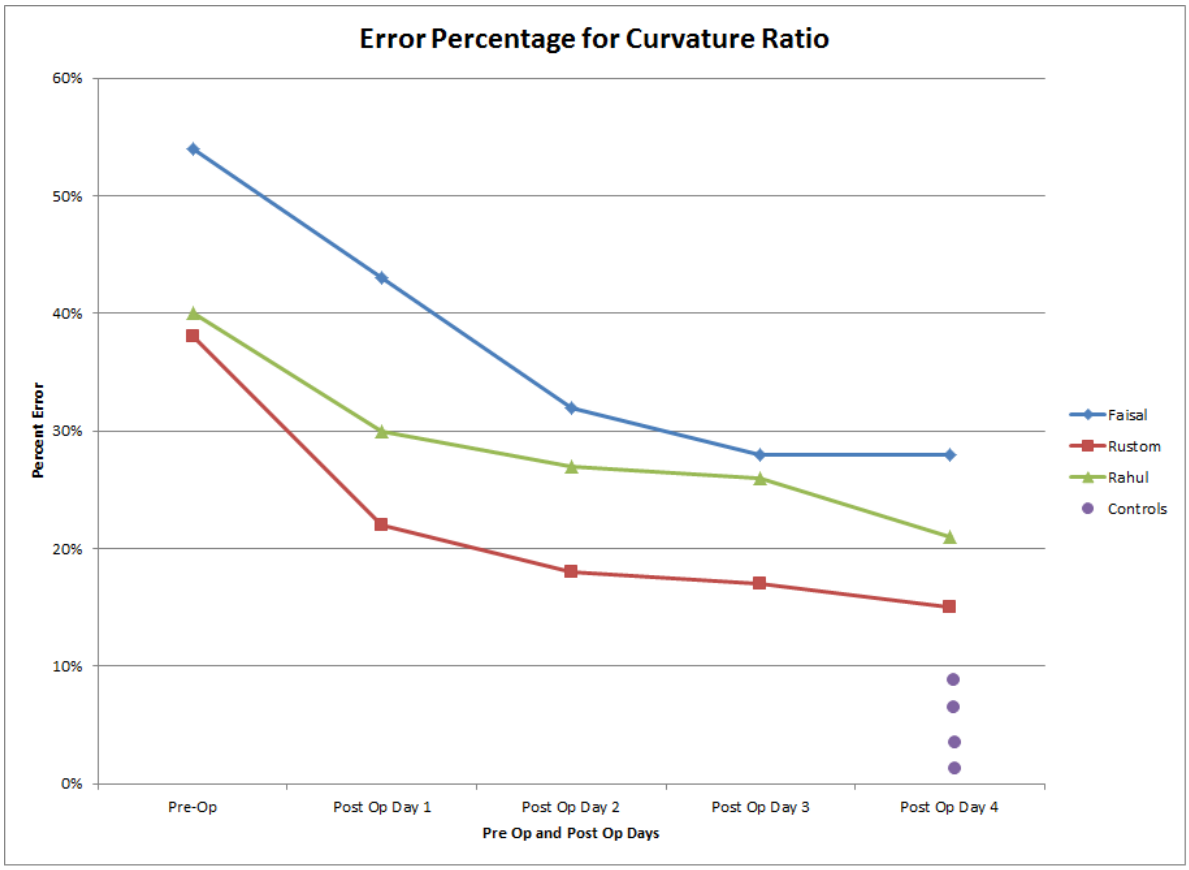


Figure 15: Error percentage for judgments of the curvature ratios of the sides of squares as a function of time in days relative to cataract replacement surgery. Note the slow improvement with time.

Figure 15 shows the error percentages incurred in the tactile-to-visual transfer of judgments about the curvature of the edges of squares. Faisal showed the largest error percentage pre-operatively at 55% while Rustom's percent error was 40% and Rahul's percent error was 38% pre operatively. Faisal and Rahul showed a 10% improvement in error percentage the day after surgery. Rustom showed a 16% decrease in errors on the day after surgery. All three patients showed a slow improvement thereafter until at day 4 their error rates were about half that of the preoperative day. The four control subjects showed less than a 10% error rate in the tactile-to-visual transfer of rectangle aspect ratio.

Table 4: Trend analysis for each patient for stick length, aspect ratio, and curvature ratio

	Faisal	Rustom	Rahul
Length	47%	30%	31%
Aspect Ratio	32%	24%	21%
Curvature	50%	32%	37%

The trend analysis table above shows the improvement seen in each of the three patients for the Length, Aspect Ratio and Curvature paradigms. Faisal's improvement was better than Rustom's and Rahul's performance in all of the three studies, perhaps because he started pre-operatively with the worst performance. All three patients showed the greatest improvement in the Curvature experiment.

Amplitude of Length, Aspect Ratio and Curvature Ratio Errors

In the previous section we have seen how the number of length, aspect ratio and curvature ratio errors decreases with time after surgery. However the amount of the individual errors can also reveal how well the patients can perform on these perceptual tasks. For example are there grossly inaccurate errors pre-surgically but only small errors post-operatively? In addition, the testing of aspect ratios and curvature are confounded by the fact that the selected shapes come in three sizes and all three sizes were presented as a group. From this data we now wish to determine how large the individual errors are and if the subjects perform better when matching the larger objects. Secondarily, we ask if they make size errors, choosing the right shape but the wrong size because the aspect ratio task and the

curvature task both tested the patients' ability to differentiate between sizes (small, medium, and large) as well as the main factor in those tests.

Lengths

The precision of cross modal perceptions of length are especially informative because the task is cognitively the simplest. Just one dimension is being tested. We can easily measure that dimension and make an absolute estimate of the tactile-to-visual transfer precision. The relative sizes of stick length are shown in figures 16 to 19. The length ranged from 1.2 cm to 12.2 cm with each increasingly long stick increasing by about 1.0 cm.

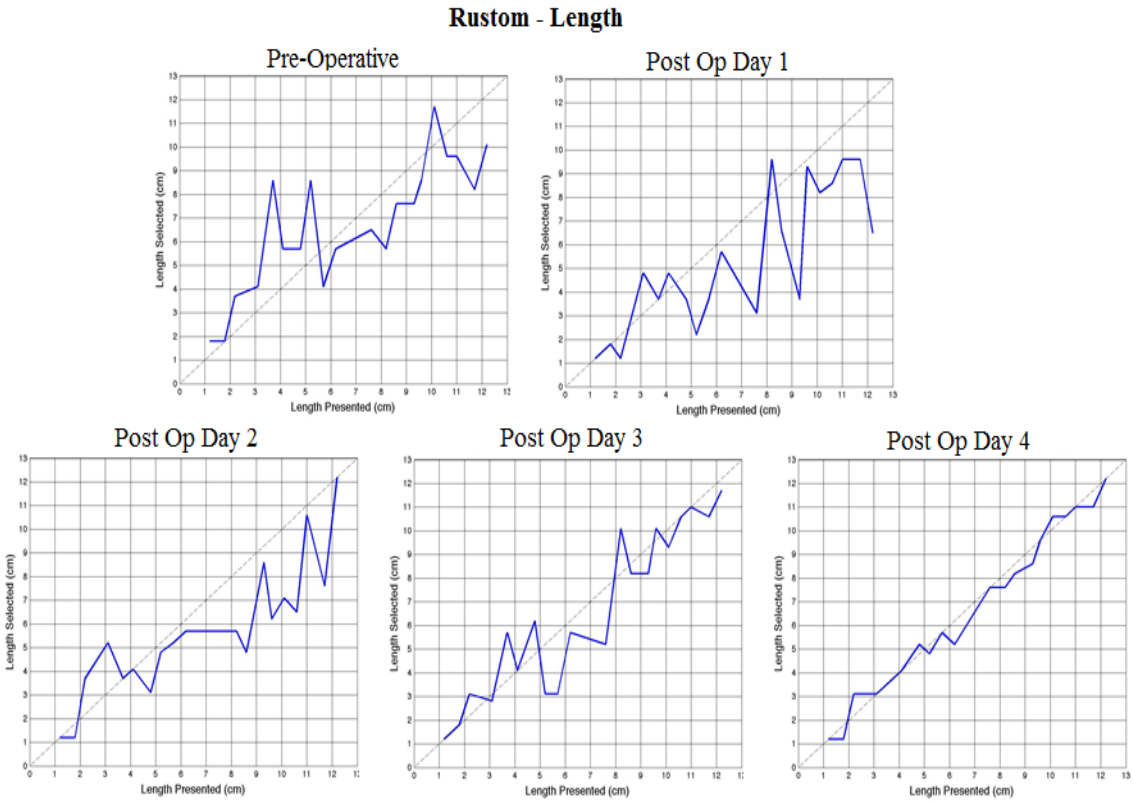


Figure 16: Amounts of Rustom's length (cm) judgment errors as a function of the actual length (cm) on successive test days. For perfect performance, the functions would be on the 45° line. On days 3 and 4 the data points have the same trend as the perfect line and the deviations from that line are relatively small.

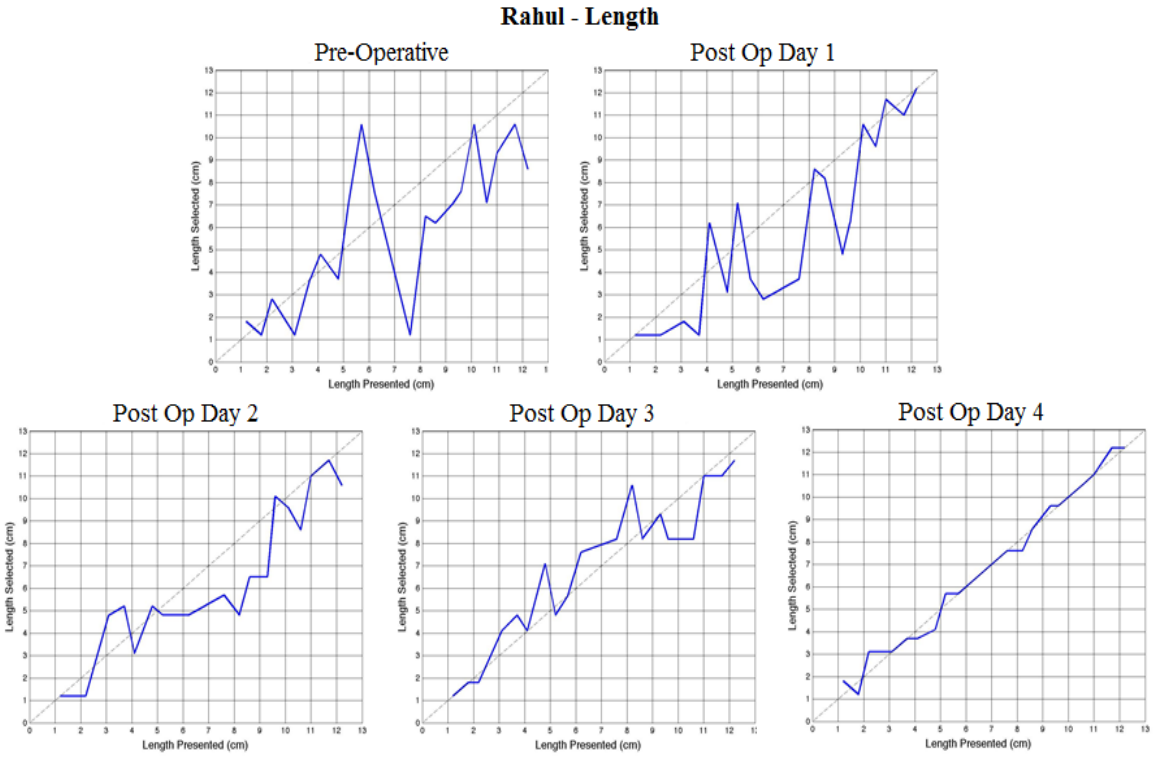


Figure 17: Amounts of Rahul's length (cm) judgment errors as a function of the actual length (cm) on successive test days. For perfect performance, the functions would be on the 45° line. On days 3 and 4 the data points have the same trend as the perfect line and the deviations from that line are relatively small.

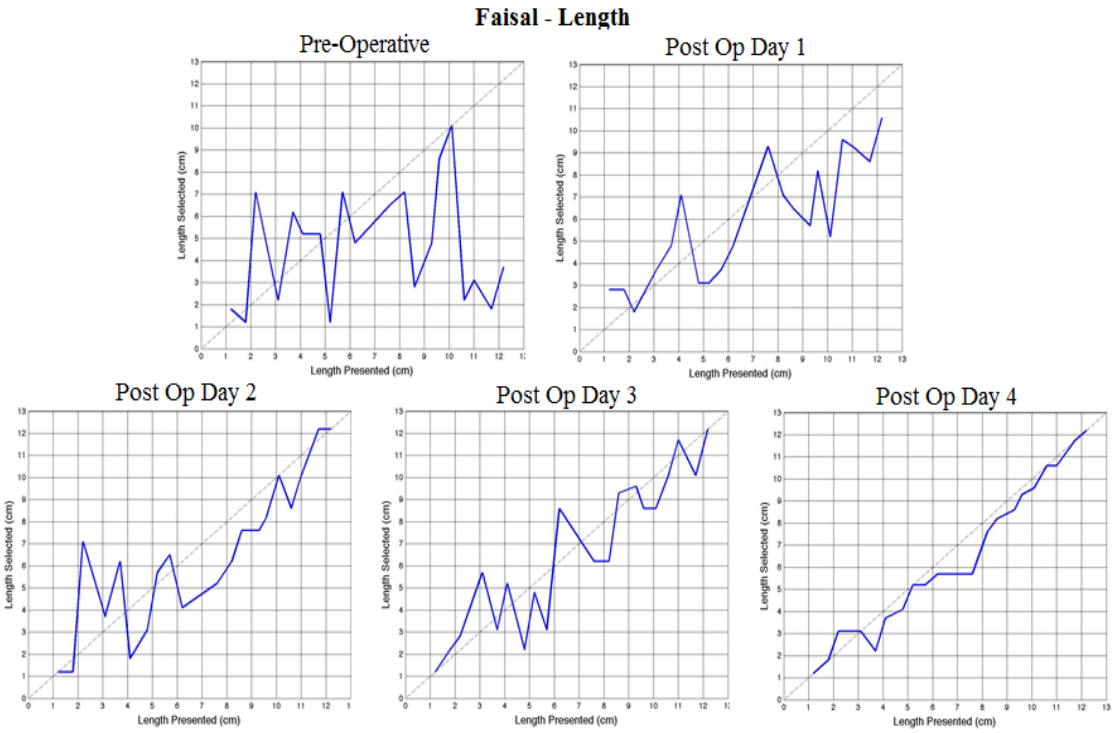


Figure 18: Amounts of Faisal's length (cm) judgment errors as a function of the actual length (cm) on successive test days. For perfect performance, the functions would be on the 45° line. On days 3 and 4 the data points have the same trend as the perfect line and the deviations from that line are relatively small.

Faisal's performance on the stick length task pre-operatively was almost random showing no trend to align with the veridical 45° line. Rustom and Rahul's judgments showed some relationship with actual stick length but still contained many large errors. Faisal, whose performance was worst, showed a significant improvement on post-op day 1. But the other two subjects showed no improvement on post-op day 1. On post-operative day 2, all showed improved performance. On post-operative day 3 the length choices were clearly correlated with actual stick length. By post-operative day 4, all three patients showed a remarkable improvement. They only erred by choosing stick lengths with the next greater or lesser stick length but never selected a stick length further removed from the actual length than this.

There performance at this time was every bit as good as that of the control subjects who had a lifetime of normal vision. The control subjects' performance was almost perfect when judging stick length except for 1 large outlier for Furquam and Hema.

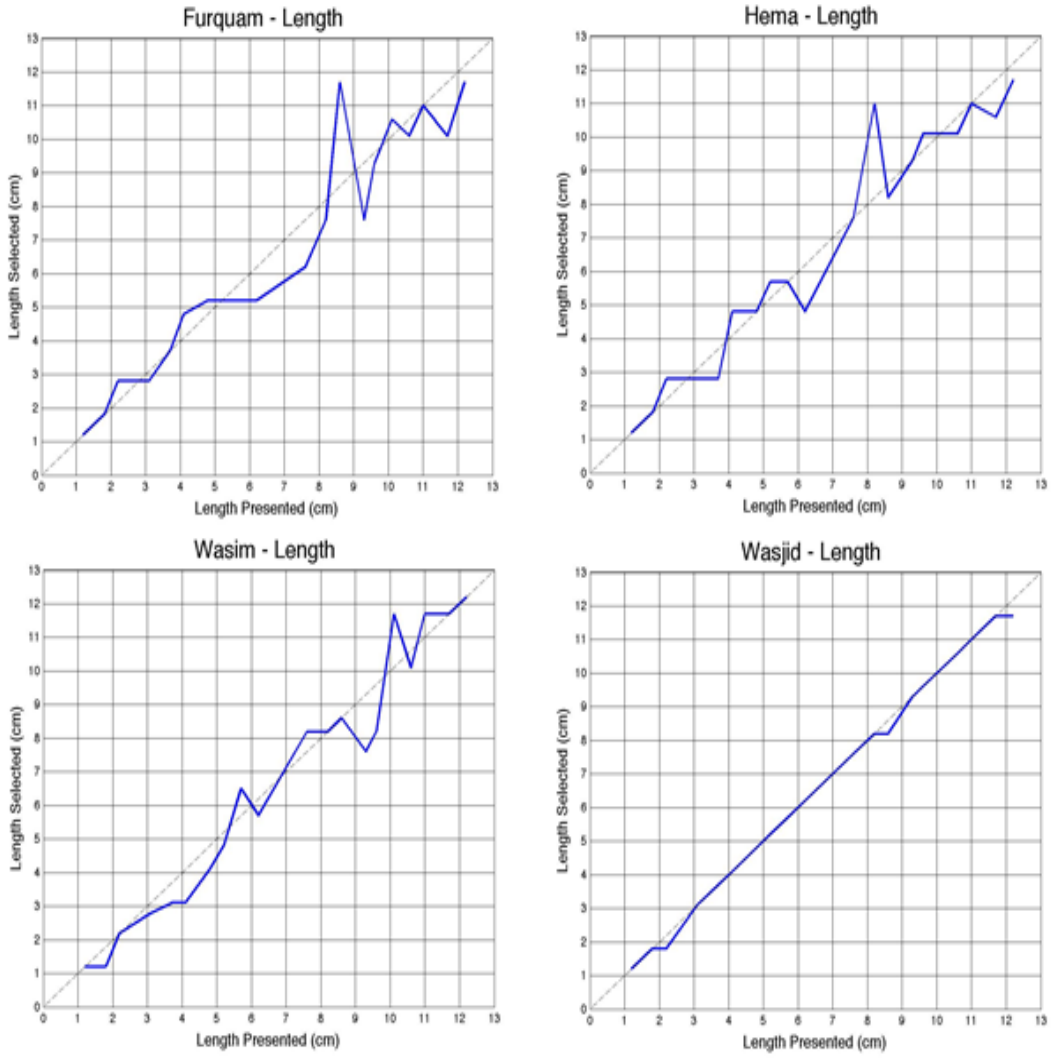


Figure 19: Amounts of length (cm) judgment errors as a function of the actual length (cm) for the 4 control subjects. For perfect performance, the functions would be on the 45° line. For the normal controls the data are close to the perfect line except for 1 large outlier for Furquam and Hema. Otherwise, the deviations from the 45° line are relatively small.

Aspect Ratios

The relative sizes of the aspect ratios are shown in figures 20 to 23. The aspect objects for the small sizes were between 1 cm to 1.5 cm, medium sizes between 1.5 cm and 2.0 cm, and large sizes between 2.0 cm and 2.5 cm. The aspect ratios ranged between 1.0 and 1.9 for all three sizes.

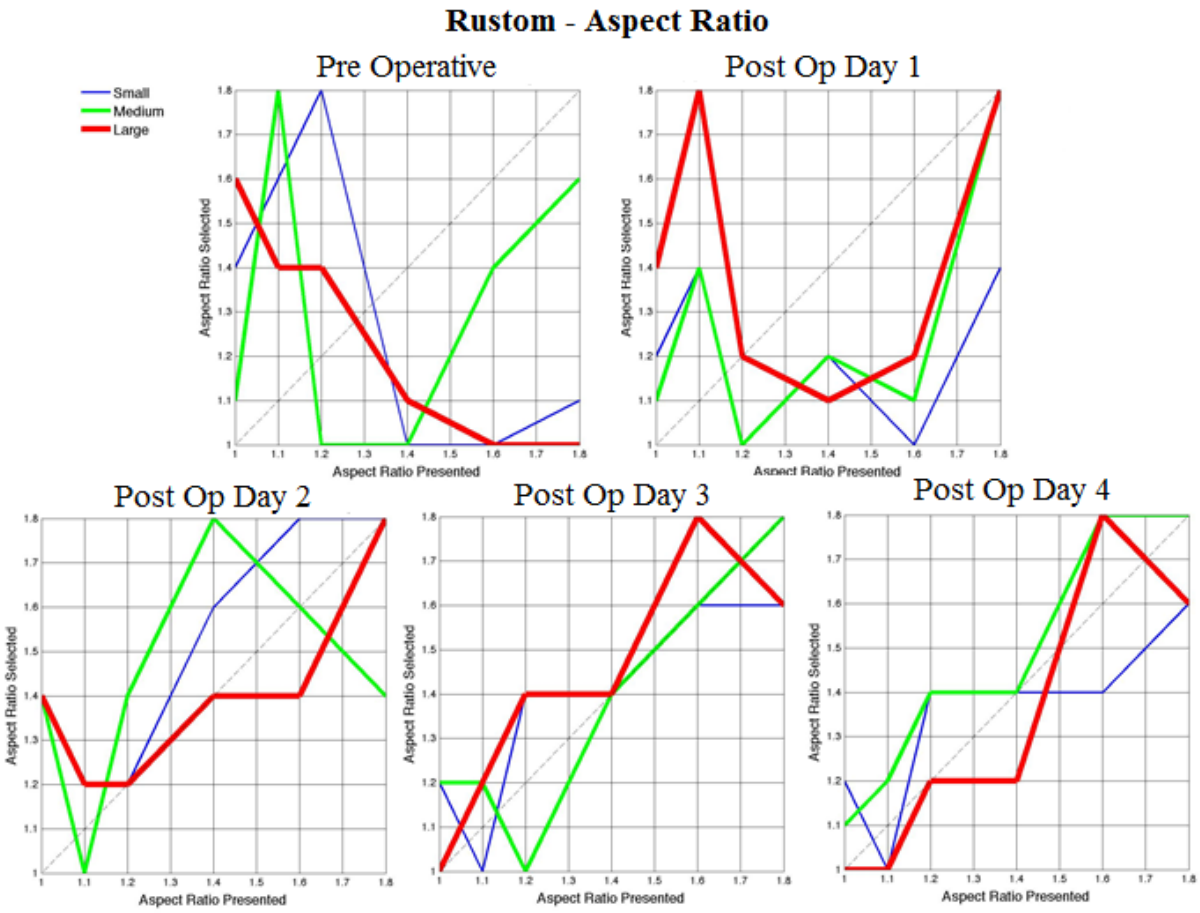


Figure 20. Amounts of Rustom's aspect ratio judgment errors for the three object sizes as a function of the actual aspect ratio on successive test days. For perfect performance, the functions would be on the 45° line. On days 3 and 4 the data points have the same trend as the perfect line and the deviations from that line are relatively small.

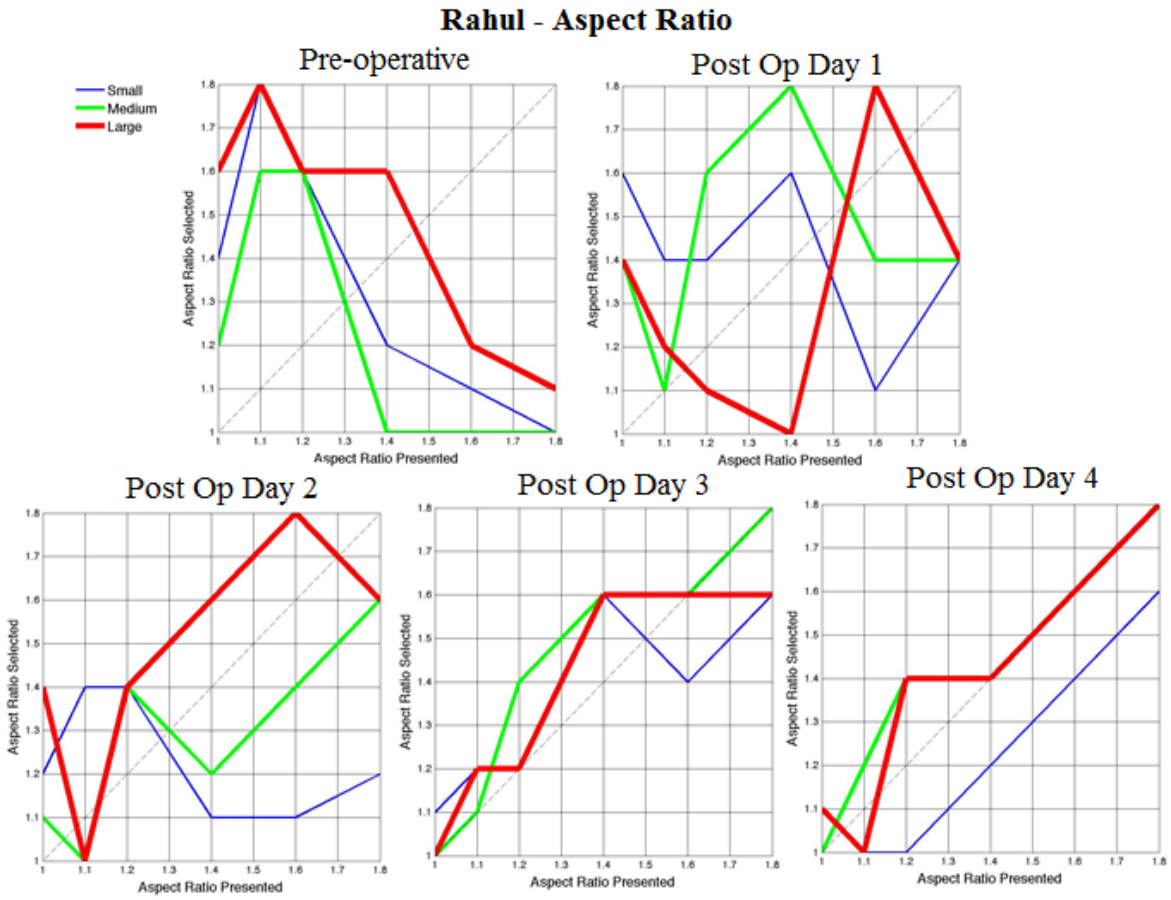


Figure 21. Amounts of Rahul's aspect ratio judgment errors for the three object sizes as a function of the actual aspect ratio on successive test days. For perfect performance, the functions would be on the 45° line. On days 3 and 4 the data points have the same trend as the perfect line and the deviations from that line are relatively small.

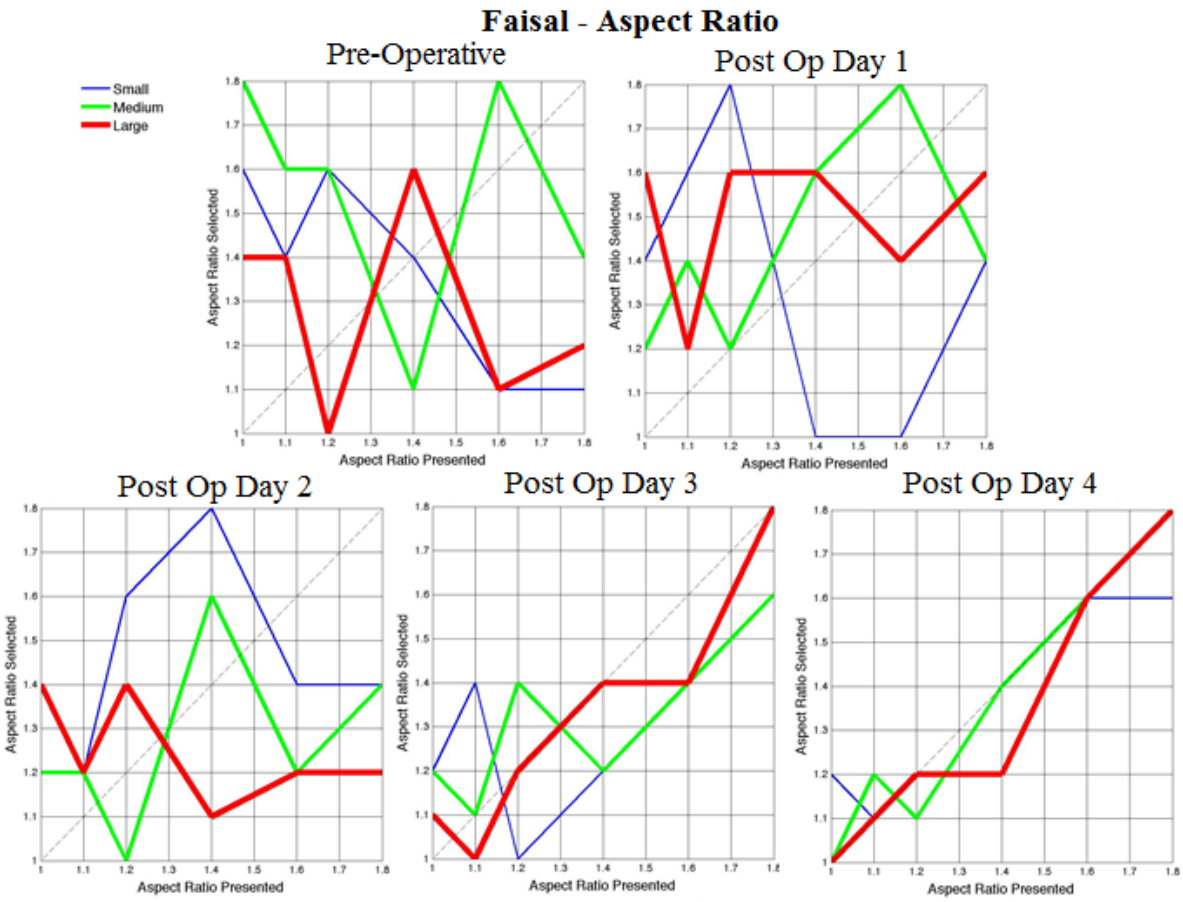


Figure 22. Amounts of Faisal's aspect ratio judgment errors for the three object sizes as a function of the actual aspect ratio on successive test days. For perfect performance, the functions would be on the 45° line. On days 3 and 4 the data points have the same trend as the perfect line and the deviations from that line are relatively small.

Overall a similar trend was observed for all the patients: their performance pre-operatively and on post-operative day 1 was almost random showing no trend to align with the veridical 45° line. On post-operative day 2, their performance improved. On post-operative days 3 and 4 the aspect ratio choices were clearly correlated with actual aspect ratios. On post-operative day 4, the patients only erred by choosing an object with the next

greater or lesser aspect ratio but never selected an aspect ratio further removed from the actual aspect ratio than this.

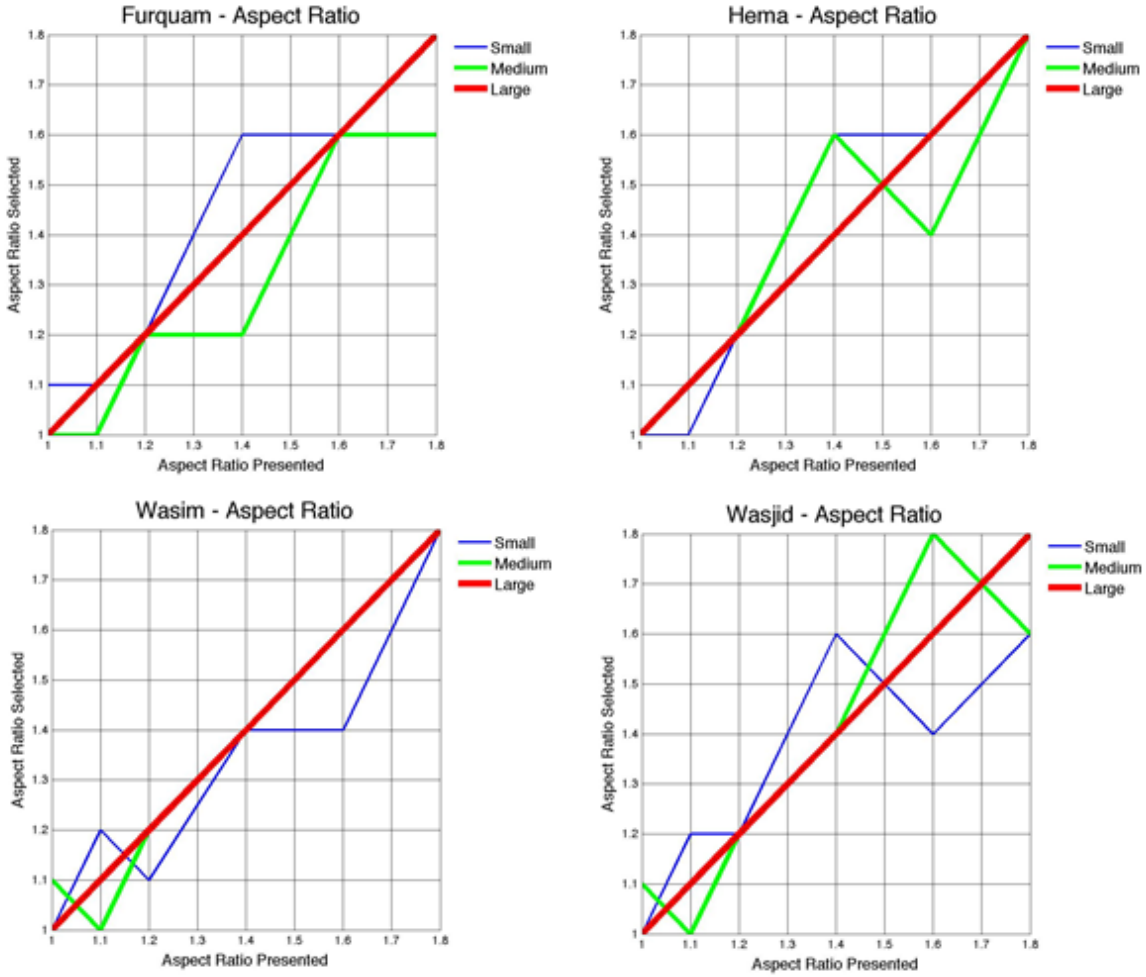


Figure 23. Amounts of aspect ratio judgment errors for the three object sizes as a function of the actual curvature ratios for the 4 control subjects. For perfect performance, the functions would be on the 45° line. For the normal controls the data are close to the perfect line and the deviations from that line are relatively small.

The control subjects' performance was perfect when judging aspect ratios of the large size objects. With the small and medium size objects they often missed by choosing an object

with the next greater or lesser aspect ratio but never selected an aspect ratio further removed than this from the actual aspect ratio.

The patients never achieved perfect performance with any size objects. By post-operative day 4 their performance with the large objects was similar to control subjects' performance with the medium and small size objects in that they often missed by choosing an object with the next greater or lesser aspect ratio. This suggests that visual resolution might be the limiting factor for patients on day 4.

Curvature Ratio

We will now present a similar analysis for the curvature ratio judgments. For the curvature objects the ratio of the average midside-to-midside distance of the object to the average corner-to-corner distance of the same object was calculated. An object with zero curvature was simply a square in which the side-to-side to corner-to-corner ratio was 0.707. A strong pincushion (inward) of curvature approaches zero and looks like the letter "x". A strong barrel curvature looks like a ball with a curvature ratio of 1.30. If the barrel distortion is even greater than a ball, the corners of the ball tend to bend inward while the sides bulge outward.

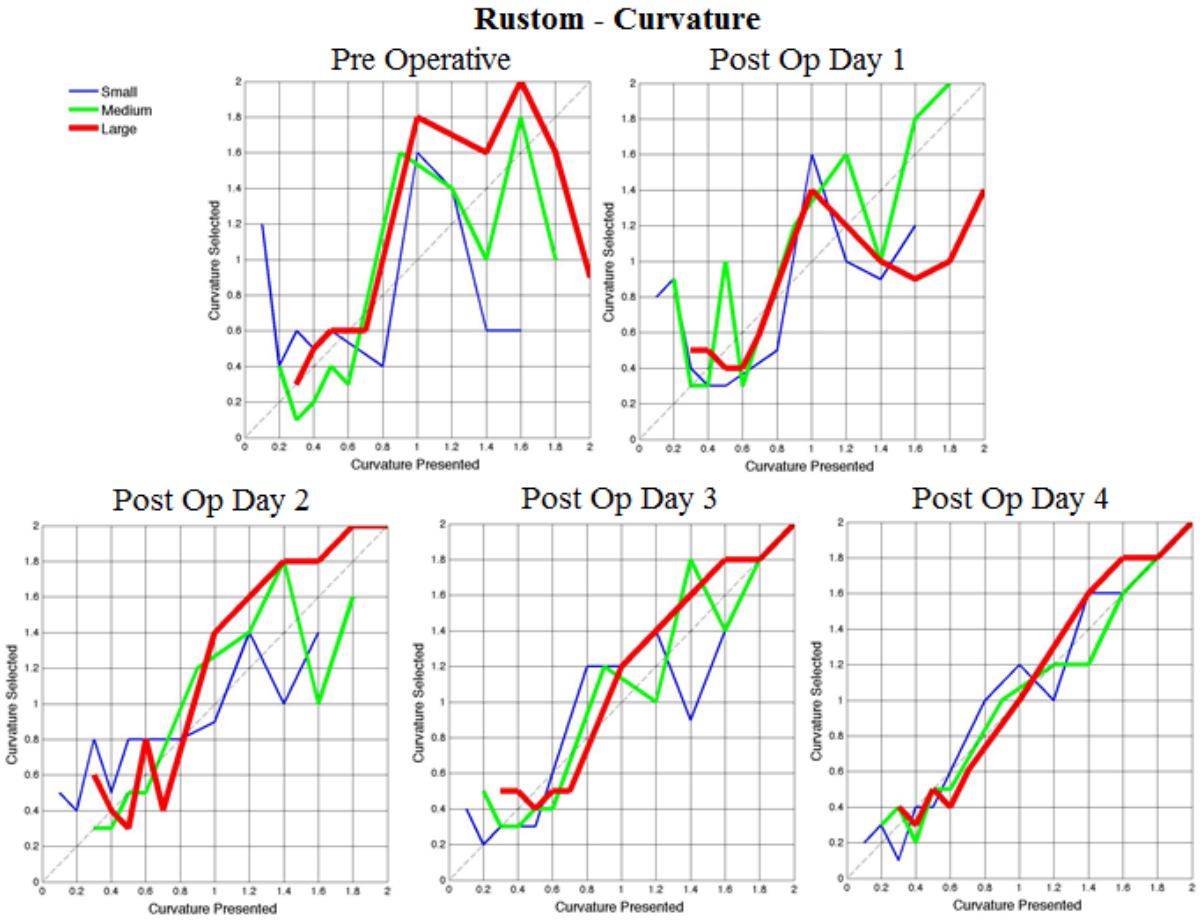


Figure 24. Amounts of Rustom's curvature ratio judgment errors for the three object sizes as a function of the actual curvature ratios on successive test days. For perfect performance, the functions would be on the 45° line. On days 3 and 4 the data points have the same trend as the perfect line and the deviations from that line are relatively small.

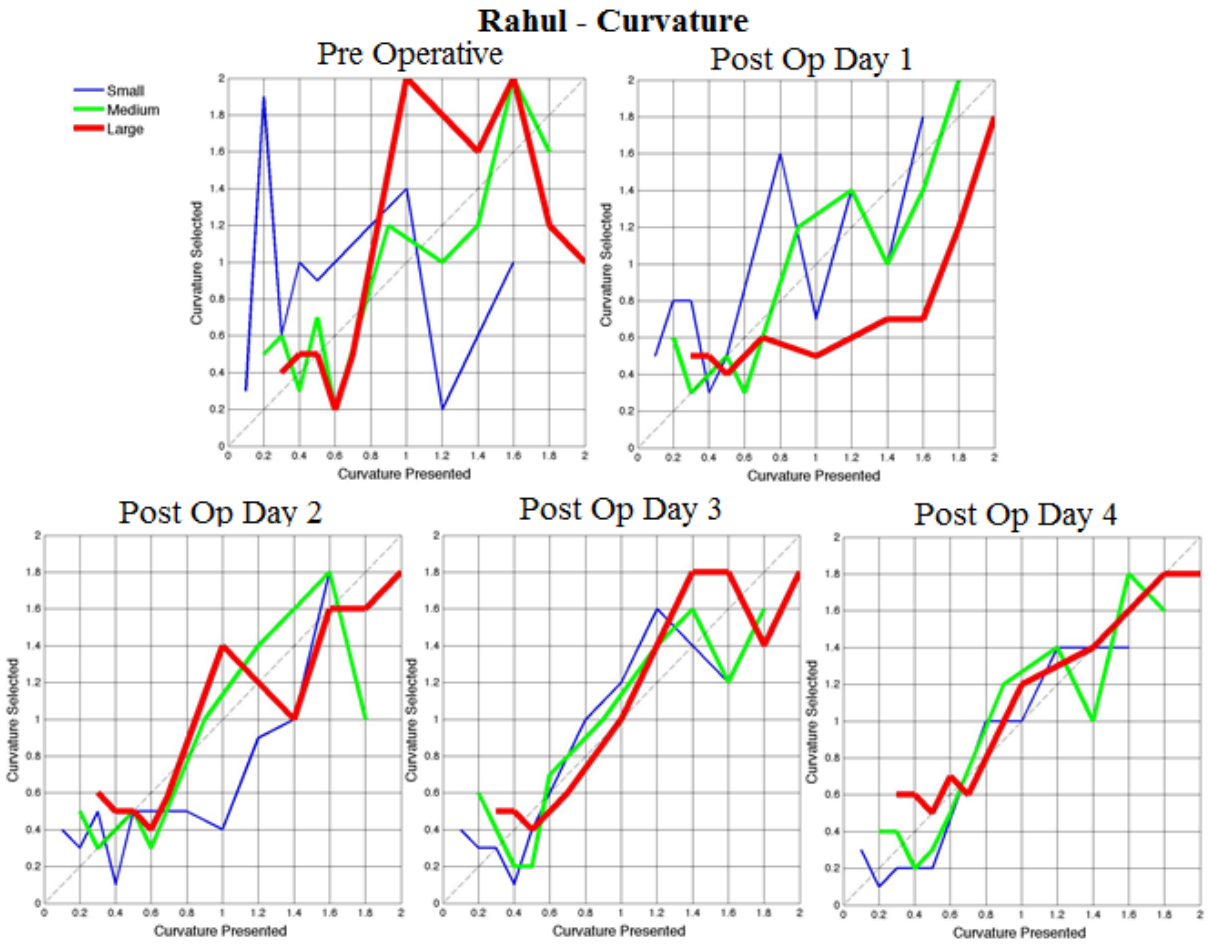


Figure 25. Amounts of Rahul's curvature ratio judgment errors for the three object sizes as a function of the actual curvature ratios on successive test days. For perfect performance, the functions would be on the 45° line. On days 3 and 4 the data points have the same trend as the perfect line and the deviations from that line are relatively small.

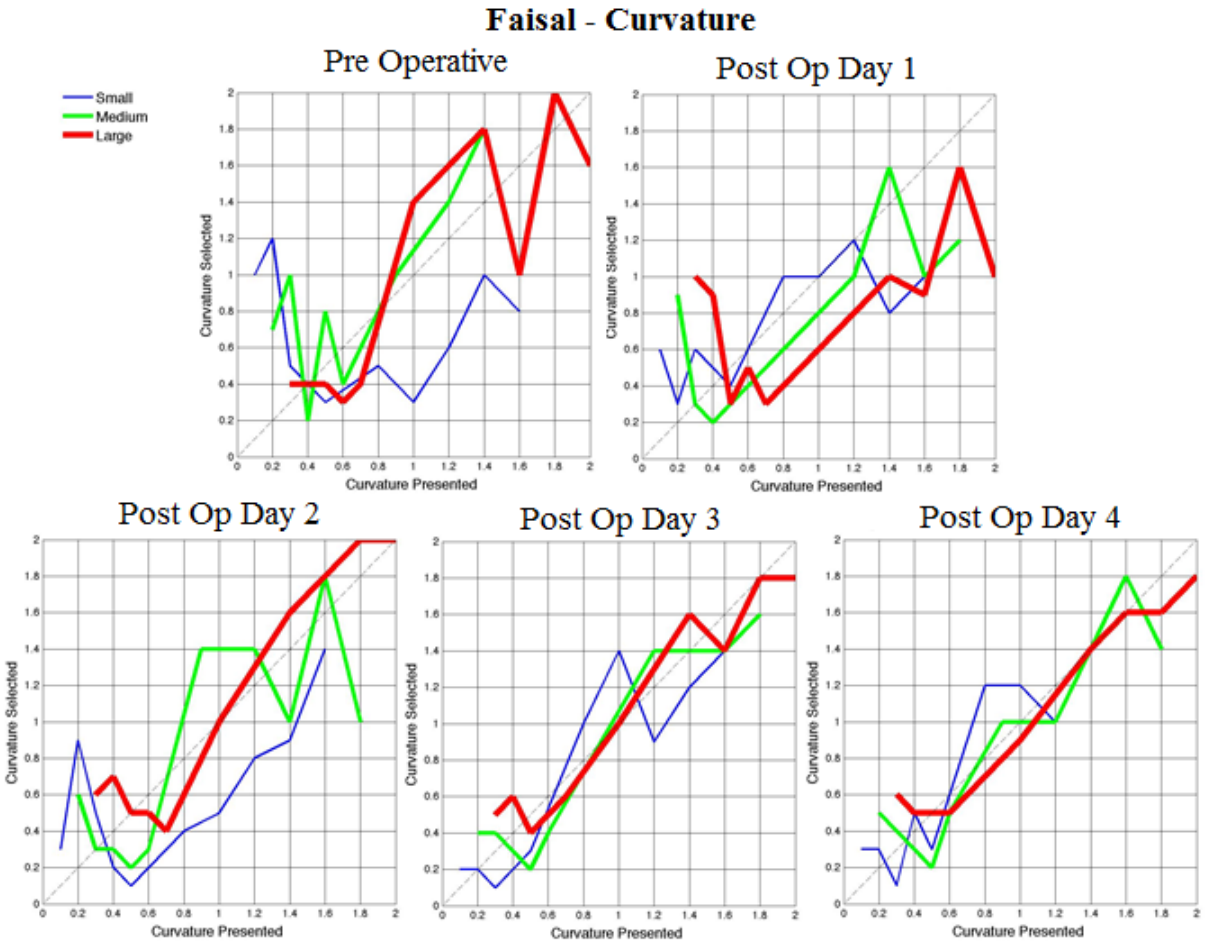
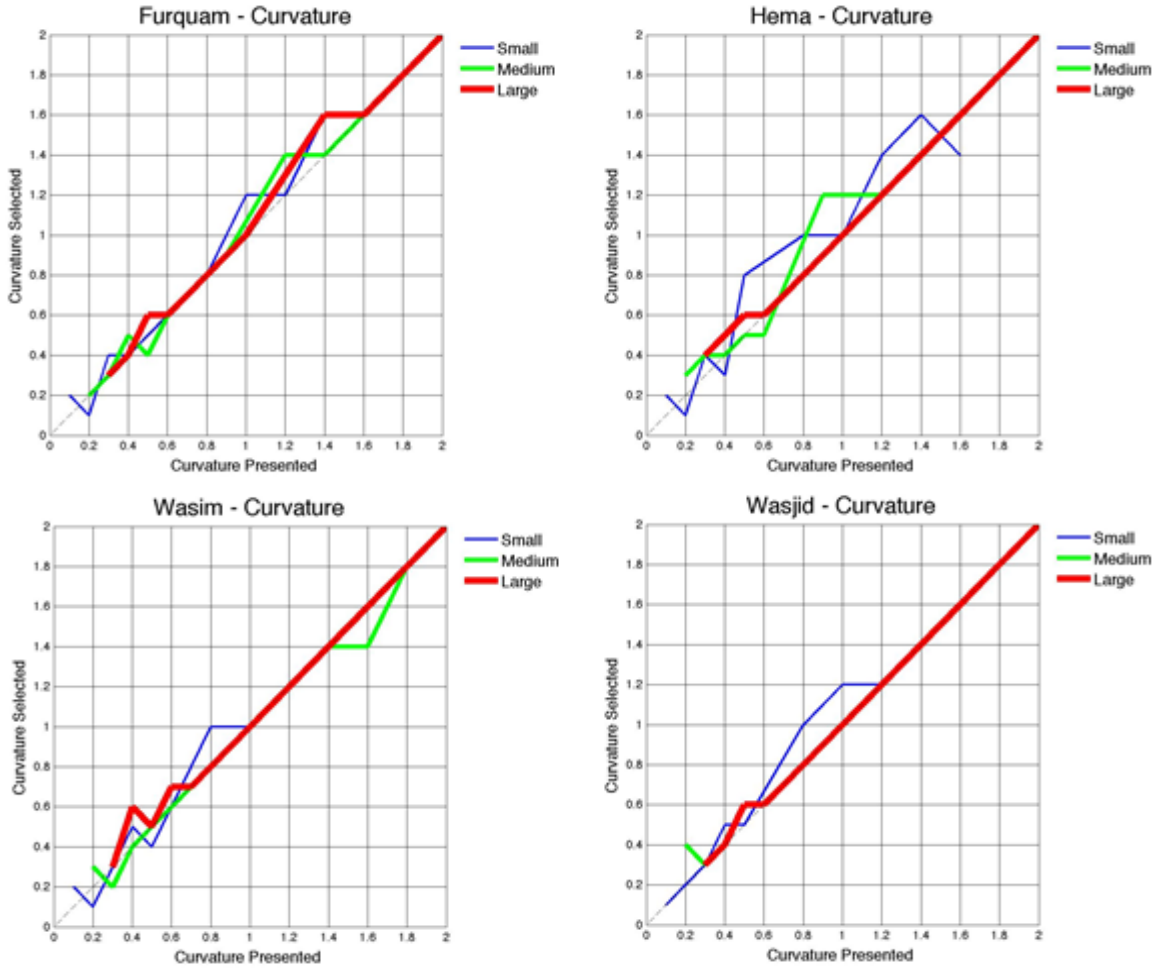


Figure 26. Amounts of Faisal's curvature ratio judgment errors for the three object sizes as a function of the actual curvature ratios on successive test days. For perfect performance, the functions would be on the 45° line. On days 3 and 4 the data points have the same trend as the perfect line and the deviations from that line are relatively small.



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Figure 27. Amounts of curvature ratio judgment errors for the three object sizes as a function of the actual curvature ratios for the 4 control subjects. For perfect performance, the functions would be on the 45° line. For the normal controls the data are close to the perfect line and the deviations from that line are relatively small.

Overall a similar trend was observed in all of the patients: their performance pre-operatively and on post-operative day 1 was almost random. On post-operative day 2, their performance improved. On post-operative days 3 and 4 the curvature choices were significantly correlated with actual curvatures. On post-operative day 4, the patients only missed by choosing an object with the next greater or lesser curvature but never selected a curvature further removed than the actual curvature than this.

The control subjects' performance was almost perfect when judging curvature of the large size objects. With the small and medium size objects they only erred by choosing an object with the next greater or lesser curvature but never selected a curvature further removed than this.

The patients never achieved a perfect performance with any size objects in the aspect ratio or curvature ratio experiments. By post-operative day 4 their performance with the large objects was similar to the control subjects' performance with the medium and small size objects in which they often erred by choosing an object with the next greater or lesser aspect ratio or curvature ratio. This suggests that similar to the length and aspect ratio experiments, visual resolution might be the limiting factor for patients on day 4.

It is important to know how often the subjects picked the wrong size objects and how often these size errors were associated with aspect and curvature ratio errors. The following table shows the percentage of size errors with the correct aspect ratio and the percentage of size errors in which the aspect ratios were also wrong.

Table 5: Size and aspect ratio errors as a function of days after surgery.

Subjects	*Size Error Only / Size & AR Errors*				
Patients	Pre-op	Post-op 1	Post-op 2	Post-op 3	Post-op 4
Rustom	0% / 26%	0%/26%	0% / 20%	7% / 13%	13% / 0%
Rahul	7% /33%	14%/33%	13%/13%	7% / 13%	0% / 7%
Faisal	13%/40%	14%/33%	0% / 47%	13%/27%	14% / 6%
Controls					
Furquam					13% / 0%
Hema					13% / 0%
Wasim					6% / 0%
Wasjid					13% / 0%

The patients made numerous size errors and when they did make a size error it was associated with an aspect ratio error 75% of the time. The control subjects made only seven size errors none of which were associated with an aspect ratio error. This indicates another aspect in which the patients made more complex errors than the control subjects.

Table 6 below shows the number of sizes errors during the curvature ratio task and the relationship of the size errors to the curvature ratio errors. The subjects made larger percentages of size errors pre operatively and their performance improved with each day of testing after surgery. The patients also made size errors associated with curvature ratios errors but unlike with the aspect ratio task few of the size errors were associated with the curvature ratios. Only 27% of the size errors were associated with curvature ratio errors. The control subjects made only seven size errors none of which were combined with a curvature ratio error. The patients gradually approached this level.

The following table shows the percentage of size errors only and the percentage of size errors associated with curvature ratio errors.

Table 6: Size only and Size plus curvature ratio errors as a function of days after surgery.

Subjects	*Size Errors Only / Size & CR Errors*				
Patients	Pre-op	Post-op 1	Post-op 2	Post-op 3	Post-op 4
Rustom	23%/10%	24%/13%	20% / 0%	17% / 0%	13% / 0%
Rahul	23%/17%	6% / 27%	24% / 3%	20% / 0%	7% / 0%
Faisal	13% / 7%	20% / 7%	20% / 7%	13% / 0%	3% / 0%
Controls					
Furquam					0% / 0%
Hema					10% / 0%
Wasim					7% / 0%
Wasjid					7% / 0%

DISCUSSION

Molyneux asked the question whether after a blind man regains his sight, can he, without touching a cube and a globe be able to distinguish them purely by sight. In other words, can a formerly blind patient who is newly sighted identify by sight (vision) the objects they experienced only by touch (tactile). Molyneux thought that a blind man cannot immediately identify by sight the objects they experienced by touch but that this skill is acquired over time.

Our experiments have answered Molyneux's question: Object recognition information from touch does not transfer to vision immediately after experiencing clear vision. But for preteen and teenage children, the intermodal link is made during the first week of clear vision. By the fourth day after cataract surgery, touch-to-vision intermodal performance accuracy and precision approaches that of normally reared children. Thus, the present experiment supports Molyneux's belief.

Prior studies have shown that cataract surgery is recommended a few months after an infant is diagnosed with congenital cataracts to obtain cross modal skills. However, the experiments conducted in the present study shows that cross modal skills improved rapidly after cataract surgery in adolescent patients. Therefore, the critical period hypothesis that neural change is not possible after about 7 to 8 years of age is not supported by the present study. The experiments conducted in this study show that partial recovery is possible well after the critical period.

Visual experience and visual recovery from congenital cataracts:

The results in the present study show that cross-modal transfer is observed to an equal degree after monocular and binocular visual experience. Waseema (Experiment 1) and Rustom (Experiment 2), who had bilateral cataract surgery just prior to testing, did not perform better than patients who had unilateral cataract extraction about one month prior to testing.

In Experiment 1, Waseema had cataract surgery in both eyes at the time of testing and we expected her to show a larger improvement than the other two children but this was not the case. The post-operative results of the monocular patients (Deepana and Vikram) vs. the bilateral patient (Waseema) did not show a clear difference in cross-modal transfer between the child who just gained binocular visual experience and the children who just gained monocular visual experience.

In Experiment 2, Rustom had cataract surgery in both eyes just before testing began. Rahul and Faisal had cataract surgery in one eye one month prior to testing and already had one month of unilateral visual experience. Yet Rahul and Faisal did not show greater improvement than Rustom on the aspect ratio or the curvature tasks. The three patients showed similar postoperative error rates. All the patients performed well post-operatively in the visual-visual condition.

Note that Experiment 1 suggests that one eye is as good as two eyes while Experiment 2 suggests that the second eye adds significant improvement to cross-modal performance. These seemingly contradictory results suggest that improvement in performance on these tasks is due to practice or learning the specific tasks tested. No matter

what the surgical history of these severely blind children their performance on the intramodal and intermodal tasks were essentially the same. The rapidity of improvement on our tasks suggests that these abilities may be somewhat slow to develop under natural conditions, but may respond well to training and therefore may be good candidates for rehabilitative exercises.

Visual and Intermodal Rehabilitation

It has been previously shown that visual rehabilitation facilitates the recovery of vision after an extended period of congenital blindness. Carlson et al (1983) carried out visual rehabilitation exercises in a patient who was treated for long lasting early blindness due to retinopathy of prematurity. Some examples of quantitative tests for visual rehabilitation included drawing a line between two points to measure visual guidance of hand movements, coloring different shapes to measure ability to perceive shapes and see contours, picking objects as quickly as possible to measure hand-eye coordination, and matching different shapes of blocks through a cover with holes of the same or different shape and blocks of the same or different sizes to measure form perception. The authors emphasize that visual rehabilitative exercises are helpful for restoring visual behavior provided that efficient visual rehabilitation is started after the corrective operation. Furthermore, they maintain that the rehabilitation should be continued long enough to assure that patients are able to function on their own (Carlson et al, 1983). Visual rehabilitative exercises are especially helpful for functioning effectively in the outside world. For example, Carlson et al's training of hand-eye coordination helped their patient to master opening the door with a key on the first trial without touching the lock (Carlson et al, 1983).

We conclude that visual rehabilitation should be carried out after measuring the initial poet-operative recovery of vision in patients with congenital blindness. In fact, visual rehabilitation on specific tasks may be as important to future success in the world as the surgery itself. The quality of life after visual rehabilitation can be assessed in future studies in Project Prakash patients and designing an appropriate rehabilitation program may be the next essential step in Project Prakash.

Project Prakash can be used to ask a number of questions raised by this and other studies. One aspect that could be tested in future tests is to ask how similar is the visual information for the two eyes that is being used by the brain. If we monocularly administer a visual recognition task to a patient with a different deprivation history for the two eyes, how readily can the patient recognize the test object with the other eye and how well can the patient perform this interocular transfer when performing an intermodal tactile to visual task. An interesting question would be: after post-critical period cataract surgery has been performed on both eyes, would the eye that had cataract surgery second be weaker in terms of visual recognition or would it be functionally equivalent to the first treated eye?

Tactile-to-tactile vs. tactile-to-visual Recognition

One interesting observation must be mentioned. Waseema is the only patient in Experiment 1 in whom cataracts were removed from both eyes at the time both intra and intermodal testing were being performed. Prior to surgery she performed perfectly on both tactile-to-tactile shape recognition tasks. After surgery her performance dropped and only improved slightly during the following week. Deepana and Vikram's performance was less

than perfect pre-surgically and showed little or no improvement after surgery. These patients had relied on their tactile sense during their early years. It was clear from the case histories and descriptions by family members that these children relied very heavily on their tactile sense. They would fan their arms out so that they would not bump into objects when walking, touch many objects in order to pick up what they wanted, etc. On first testing the patients performed near chance on the tactile-visual, visual-tactile, and visual-visual shape recognition tasks preoperatively.

So the question is what happened to Waseema's tactile-to-tactile object recognition ability after cataract removal. Waseema's visual-to-visual skills showed a slight improvement between pre-operative testing and day 1 of post-operative testing. Fine (2003) reported the behavior of a patient who was an expert skier earlier in earlier in life while blind. Immediately after cataract removal, this patient would close his eyes when skiing. He said he did this because the visual information gave him a frightening sense of collision. Another patient was confident crossing the street when he was blind but became frightened as soon as he regained sight. After regaining sight in both eyes, Waseema seemed to perform poorly in the tactile-to-tactile task. Perhaps as Waseema's visual experience was strengthening her visual system, the strengthened visual system may have interfered with her tactile-to-tactile skills.

Held (2009) has proposed that coupling between the tactile and visual signals must occur for cross-modal transfer to occur during later processing levels. It can be hypothesized that plasticity between the tactile and visual maps were slowly reforming once Waseema regained sight. Bower et al examined development of touch and vision in infants. The

specific question they asked is whether vision precedes touch or whether touch precedes vision as the dominant sense. The results showed that the visual system has more control over infants' skills of grasping objects at an early age compared to the tactile system. However at about 5 months of age, results show that the tactual system becomes more rapid in its operation because of maturation. Therefore, the visual system anticipates an action and the tactile system takes control after an object is in hand (Bower, Broughton, and Moore, 1970). Waseema's tactile system was dominant prior to cataract surgery. Her performance in the tactile-to-tactile task briefly declined after cataract surgery. We know that the tactile and visual system are learning to work together after sight is restored but will this intermodal enhancement help restore the tactile recognition system to full strength? In future studies, the Project Prakash patients should be examined over many months to compare the development of their tactile and visual systems after many years of blindness.

Comparison of task difficulties

The results of experiments like these in this thesis always depend on the difficulty of a task. If we had selected objects that barely differed from each other (that is, that were very difficult for normally reared children to discriminate between) we might have found chance levels of performance and no improvement with testing. If we had selected very different objects such as recognizing a basketball versus a Lego block, we might have found immediate perfect learning. We have tried to find a middle course in which there is neither a strong ceiling effect nor a strong basement effect. The objects we have chosen differed by amounts typical of the discriminations we must make in real life and fortunately led to a

range of responses that allow us differentiate the patients' performance abilities throughout the learning period.

There were a number of factors that may have influenced the relative ease of the different object recognition tasks we used. The most obvious extraneous cue is the colors of the Lego blocks. The congenitally blind cataract patients are known to have color vision so we might expect color differences to help the vision-to-vision task. The data reveals that color was likely not used because patients' vision-to-vision performance on the Lego and curvature tasks improved to an equal degree over time. If color had been a factor, performance in the vision-to-vision task would have been better compared to the curvature experiment.

A second factor that might have affected performance is the number of choices made available to the patients after first inspecting one of the objects. In human blind-sight and in animal experiments subjects can perform almost perfectly in two choice recognition tasks but perform at chance if more than four or five choices are presented (Weiskrantz, Barbur, and Sahraie, 1995; Weiskrantz & Cowey, 1975). Our subjects have never seen forms and are blind by most standards so they might be more like Weiskrantz' subjects than normal observers. In Experiment 1, there were 15 Lego block shapes and 10 curvature shapes. Thus, the curvature task might be expected to be slightly easier especially since the 5 pincushion objects had sharp corners and the 5 barrel objects had rounded corners so the two halves would be readily discriminated from each other. The Lego test had 15 shapes of random configurations and patients had to distinguish the pattern of bumps on the Lego blocks and their sizes. The patients had to remember the specific configurations of each shape. The

subjects performed about equally on the two tasks so the number of objects may not have been a factor.

In Experiment 2, the three tasks used a large number of object choices that differed for the three tasks. Stick Length had 23 objects, Aspect Ratio had 18 objects and Curvature Ratio had 30 objects. This might have made the curvature task more difficult compared to the others. However the patients' performance when measured with the size of the errors in the length, aspect ratio, and curvature ratio tasks gradually decreased similarly after cataract surgery. An interesting trend when the sizes of the errors were measured was that patients never achieved a perfect performance with any size objects in the aspect ratio or curvature ratio tasks. The patients' performance on post-operative day 4 with the largest objects was similar to the control subjects' performance with the medium and small size objects in which they often erred by choosing an object with the next greater or lesser aspect ratio or curvature ratio. This suggests that visual resolution or tactile resolution might be limiting factors for patients on the final day.

In future experiments, one set of sizes should be shown for a given trial for both the aspect ratio and curvature ratio tasks. With the present stimuli this means that 6 aspect ratios would be shown during a trial and 10 curvature ratio objects would be shown during a trial. We think the aspect ratio forms might be increased to 8 and the curvature ratio objects reduced to 8 on a given trial to eliminate size and the number of choices as a factor in the decision making process. It is obviously interesting to use the different size objects to

examine how object size effects performance. The simplified sets during each trial will clarify the interpretation of size effect.

Visual Acuity and visual resolution

Visual acuity is the usual measurement cited by clinicians for visual improvement but we have barely cited it in this thesis. This is because the assessment of visual acuity was inconsistent and referred only to finger counting distance. The ability to finger count is not really a visual resolution task and it may be considered another an example of cross-modal transfer. The patients must visually examine how many fingers the experimenter held up and provide an accurate answer. One observation was that prior to cataract surgery the patients were trying to count fingers by touching the experimenter's hands. This was likely an innate skill that children with visual impairment use. After the cataract surgery, the patients relied less on their tactile skills. They used their vision to identify how many fingers the experimenter held up after cataract surgery was performed.

Limitations

Cross modal studies shed light on how humans develop their visual abilities as well as how different senses communicate with each other. An important limitation in the present study is that patients could not be tested on a longitudinal basis after they were discharged from the hospital. Fortunately, the subjects showed such remarkable recovery during the first week that we were able to document most of the recovery process during that one week. In the future, a longitudinal study should be carried out to assess the full time frame for the

development of cross-modal links and whether the patients can eventually achieve normal levels of cross-modal linkage.

Another limitation in our study is the small sample size. This is due to the fact that this is a rare subset of patients who are found only in rural villages and our patients had to match relatively strict inclusion criteria. Any future experimental studies using patients who are blind due to dense bilateral congenital cataracts are unlikely to have larger samples.

Additional limitations are that since patients come from underprivileged areas, many of them could not read letters, numbers or recognize shapes. Therefore, the experiments had to be modified to get accurate results from these children. There was also a language barrier but this problem was partially solved by having a translator when possible. Another limitation is that the case history had to be based on what the family reported, including density and onset age of cataracts. For example, pictures taken during childhood may have helped us assess the density of cataracts earlier in life but no pictures could be taken by these families. This would have helped categorize our patients to provide more accurate comparisons among them. One other limitation was the scheduling of patients to come to the hospital for testing and follow-up. Due to extreme summer heat in Delhi and the lack of transportation from the villages, testing and follow-up appointments sometimes had to be changed. One of the patients in the study had to take time off for a death in the family and could not be examined during the few weeks he was absent.

CONCLUSIONS

Our patients and their families had goals to go to school, help with chores around the house, be able to groom themselves, help family with outdoor work, doing shopping, etcetera. Cataract extraction after many years of blindness may not necessarily provide ‘perfect’ vision. However, the results of our study show that functional vision is attainable and that there is immediate improvement during the first week.

Despite their limitations, the children who get late treatment for congenital cataracts have shown that there is not an absolute critical-period to regain visual function after many years of blindness. We have heard back from these children that they are able to function well in their environment. Many of the children who were not able to attend school due to blindness are attending school following surgery. The present study shows that the nervous system retains plasticity beyond 7 or 8 years of age. Therefore, surgical treatment for congenital cataracts should be provided for adolescents.

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