Mushroom body output neurons encode valence and guide memory-based action selection in Drosophila. Elife 3, e04580.

15. Feinberg, E.H., Vanhoven, M.K., Bendesky, A., Wang, G., Fetter, R.D., Shen, K., and Bargmann, C.I. (2008). GFP reconstitution across synaptic partners (GRASP) defines cell contacts and synapses in living nervous systems. Neuron 57, 353–363.

16. Owald, D., Felsenberg, J., Talbot, C.B., Das, G., Perisse, E., Huetteroth, W., and Waddell, S. (2015). Activity of defined mushroom body output neurons underlies learned olfactory behavior in Drosophila. Neuron 86, 417–427.

17. Bouzaiane, E., Trannoy, S., Scheunemann, L., Plaçais, P.Y., and Preat, T. (2015). Two independent mushroom body output circuits retrieve the six discrete components of Drosophila aversive memory. Cell Rep. 11, 1280–1292.

18. Ramdya, P., Lichocki, P., Cruchet, S., Frisch, L., Tse, W., Floreano, D., and Benton, R. (2015). Mechanosensory interactions drive collective behaviour in Drosophila. Nature 519, 233–236.

19. Wasserman, S.M., Aptekar, J.W., Lu, P., Nguyen, J., Wang, A.L., Keles, M.F., Grygoruk, A., Krantz, D.E., Larsen, C., and Frye, M.A. (2015). Olfactory neuromodulation of motion vision circuitry in Drosophila. Curr. Biol. 25, 467–472.

20. Fischler, W., Kong, P., Marella, S., and Scott, K. (2007). The detection of carbonation by the Drosophila gustatory system. Nature 448, 1054–1057.

Neuroplasticity: Unexpected Consequences of Early Blindness

Micah M. Murray[1,2,3,4,*], Pawel J. Matusz[1,5,6], and Amir Amedi[7,8,9,*]
[1]The Laboratory for Investigative Neurophysiology (The LINE), Department of Radiology & Department of Clinical Neurosciences, University Hospital Centre and University of Lausanne, Lausanne, Switzerland
[2]The Electroencephalography Brain Mapping Core, Centre for Biomedical Imaging (CIBM), University Hospital Centre and University of Lausanne, Lausanne, Switzerland
[3]Department of Ophthalmology, University of Lausanne, Jules-Gonin Eye Hospital, Lausanne, Switzerland
[4]Department of Hearing and Speech Sciences, Vanderbilt University, Nashville, TN 37232, USA
[5]University of Social Sciences and Humanities, Faculty in Wroclaw, Wroclaw, Poland
[6]Attention, Brain and Cognitive Development Group, Department of Experimental Psychology, University of Oxford, Oxford, UK
[7]Department of Medical Neurobiology, Institute for Medical Research Israel-Canada (IMRIC), Hadassah Medical School, Hebrew University of Jerusalem, Jerusalem, Israel
[8]The Edmond & Lily Safra Centre for Brain Sciences (ELSC), and Cognitive Science Program Hebrew University of Jerusalem, Jerusalem, Israel
[9]Sorbonne Universités, UPMC Univ Paris 06, Institut de la Vision, UMR_S 968, Paris, F-75012, France
*Correspondence: micah.murray@chuv.ch (M.M.M.), amir.amedi@ekmd.huji.ac.il (A.A.)
http://dx.doi.org/10.1016/j.cub.2015.08.054

A pair of recent studies shows that congenital blindness can have significant consequences for the functioning of the visual system after sight restoration, particularly if that restoration is delayed.

Cataracts cause one third of all cases of blindness worldwide [1]. Although nowadays cataracts are readily treated surgically (and potentially in the near future even using eye-drops [2]), these techniques are not equally accessible worldwide. The case of Claude Monet, who went blind late in life, illustrates the debilitating consequences of cataracts (Figure 1). Was Monet genetically predisposed to be the originator of impressionism, or was his pioneering role as a painter influenced by a critical period of visual development? What would he have painted if he had been blind during childhood? Disentangling the respective contributions of biological constraints and experience and their neural bases are important challenges for neuroscientists. The visual system has long been used as a model to study this so-called nature–nurture debate: is one born an impressionist master or can this be learnt? Two recent studies [3,4] in *Current Biology* addressed precisely how early-life blindness reorganises the brain and influences the ability to see again after corrective surgery. Which functions are innate, which require early-life experience, and which can be (re)trained at any time in life?

McKyton *et al.* [3] show that, while sight-restored individuals can see, they do not always perceive occlusion between objects. Thus, certain visual functions rely on the integrity of sight during early life and seem to not be restored even after sight recovery (unless, possibly, following specialised training; see below). Collignon *et al.* [4] demonstrate how hearing recruits otherwise visual brain regions following just short-term loss of vision during early life. Their findings show that early crossmodal reorganisation can persist into adulthood, years after vision has been restored. Together, these studies not only provide new insights regarding optimal times for developing brain functions, but also emphasise how brain plasticity extends across canonical boundaries between the senses.

Part of Hubel and Wiesel's Nobel prize-winning research revealed that 'critical periods' — time intervals beyond which a function is either never acquired or, if it is

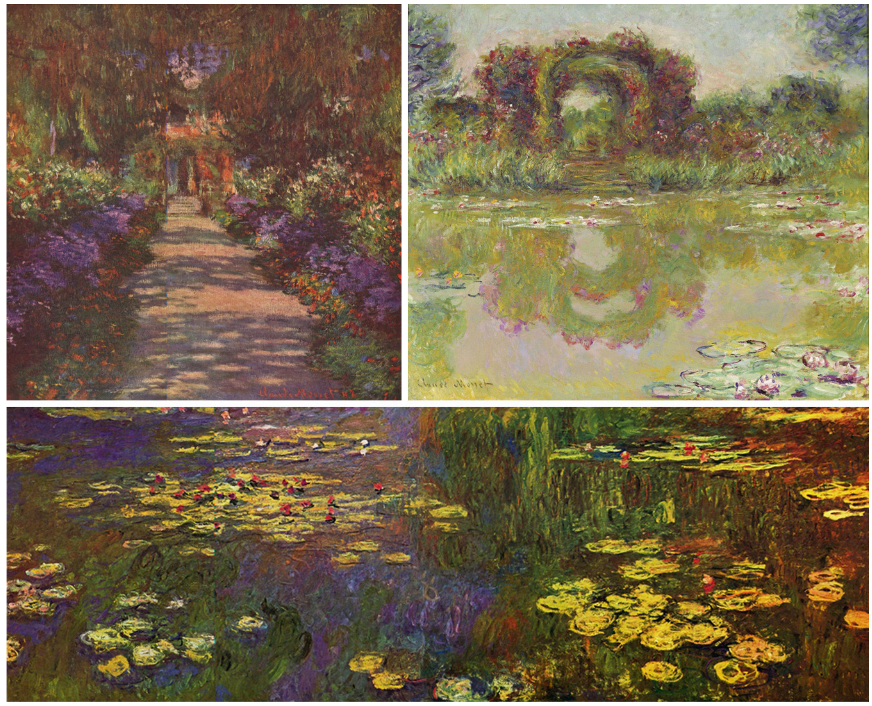

Figure 1. Beauty is in the eye of the beholder.
These paintings by Claude Monet (1840–1926) show how his work changed across the final quarter century of his life. The left image (*Pathway in Monet's Garden at Giverny*, 1901–1902) was painted at the age of 61. The right image (*Rose Arches at Giverny*, 1913) was painted after Monet's diagnosis with cataracts. The bottom image (*Water Lilies*, 1920–1926) was painted during the period just prior to and after his surgery, which was performed in 1923. Monet was himself clearly torn by the consequences after his surgery: in a letter to the doctor who performed the surgery he wrote: "*I might have finished the Decorations which I have to deliver in April and I'm certain now that I won't be able to finish them as I'd have liked. That's the greatest blow I could have had, and it makes me sorry that I ever decided to go ahead with that fatal operation. Excuse me for being so frank and allow me to say that I think it's criminal to have placed me in such a predicament*." (Letter to Doctor Charles Coutela, June 22, 1923 Giverny). All the same, Monet's sight was also clearly enhanced; he described how "*Color is my day-long obsession, joy and torment. To such an extent indeed that one day […] I caught myself in the act of focusing on her temples and automatically analyzing the succession of appropriately graded colors […]*." (Claude Monet: Les Nymphéas (1926) by Georges Clemenceau, Ch. 2). Top left and bottom images: The Yorck Project. All images: Wikimedia Commons.

acquired, it is deficient in some severe way — characterise the development of brain circuits [5]. While animal studies provide one way to parametrically investigate the importance of critical periods for sensory functions [6], similar work in humans meets obvious ethical constraints. Children born with cataracts thus present a unique opportunity, particularly when they are born in countries where surgical correction may not be readily available. Pioneering projects (http://prakashcenter.org/projectprakash/) [7] are not only helping to treat blind children in the developing world, but also paving the way for the more rigorous investigations of visual function development and neural plasticity in humans, such as those discussed here.

McKyton *et al.* [3] tested visual functions regained after years of visual deprivation. They studied 11 Ethiopian children and teenagers who were ~5–10 years old when their cataracts were operated and then tested either immediately after recovery from the surgery or up to 7 years post-surgery. The authors targeted specifically low-level and mid-level visual functions: the former being discriminations based on colour, size, or shape; and the latter shape discriminations based on occlusion, shading, orientation, or illusory contours. Earlier studies had been limited either to single cases or to intermingled low-level and mid-level vision contributions.

McKyton *et al.*'s [3] patients could successfully perform the low-level vision tasks, but their mid-level functions were overall impaired when compared to those of sighted controls (who viewed highly blurred versions of the stimuli as a way of equalising contrast-sensitivity functions across groups). By contrast, a 'comparison' group of patients with cataracts corrected within the first two years of life (and tested 3–13 years later) performed well on both kinds of tasks. Thus, McKyton *et al.* [3] provide the first evidence showing how critical early cataract correction is for the healthy development of skills enabling object discrimination in naturalistic viewing conditions.

Certain aspects of the McKyton *et al.* [3] study, however, require qualification. Most notably, there was considerable variability across the patients and tasks. Patients' performance frequently followed a bimodal distribution: when discriminating objects defined by illusory contours (see [8] for a review of neural mechanisms) some patients performed at near-ceiling levels (similar to controls), while others performed at roughly chance levels. Other illusions seem more resilient to early-life blindness: another study [9] reported recently in *Current Biology* actually found that 100% of newly-sighted children and teenagers tested within two months of their sight-restoration surgeries were sensitive to visual illusions of perceived size.

Generally, to understand the real extent of visual deprivation driving cortical reorganisation, it is fundamental to establish as precisely as possible the level of pre-surgical vision in newly-sighted individuals. To qualify for corrective surgery, light sensitivity must be intact, indicative of a partially active retino-geniculo-striatal pathway. This may explain how some visual functions are so rapidly restored.

Another consideration is the degree of experience-dependence of the studied visual functions. The oddball-discrimination tasks used by McKyton *et al.* [3] may have tapped into experience-dependent processes [10], in contrast to the illusions reported in Gandhi *et al.* [9]. The role of experience can indeed be profound, a point emphasised by the way that what is nominally a visual function can be mediated entirely by inputs from another sensory modality (see below). Because objects and their semantics are also experienced through other senses, particularly in visually-impaired children, mental representations may be established from which to draw upon after sight-restoration (though with limits, see [11]). Such considerations notwithstanding, the study of McKyton *et al.* [3] provides important new insights into the types of visual functions that are robust against early-life sensory deprivation.

Collignon *et al.* [4] provide similarly important contributions to the debated role of critical periods in brain plasticity. Inspired by the fact that congenital, irreversible blindness drives the occipital cortex — typically devoted to vision — to respond to auditory stimulation [12], the authors reasoned that a limited period of early-life visual deprivation might suffice to trigger life-long crossmodal reorganisation. Their participants performed two duration-judgment tasks, involving either voices or horizontally moving sounds, while functional magnetic resonance imaging data were acquired. The findings are in line with the role of critical periods in brain plasticity: sound-induced activity was found to be enhanced, relative to sighted controls, within the cuneus portion of occipital cortices of the 11 Canadian adults who had experienced short-term (9–238 days) visual deprivation at birth as a result of dense bilateral cataracts.

A major strength of the Collignon *et al.* [4] study is careful control of the patients' history; this is particularly important as light perception is frequently present in cataract patients to varying degrees despite impaired or absent pattern vision. Moreover, the loci of the effects did not vary across the two auditory tasks; this lack of task selectivity may be driven by the short duration of the visual deprivation (see, for example, [12] for a review of effects of longer visual deprivation). Lastly, Collignon *et al.* [4] employed state-of-the-art functional connectivity and demonstrated a cortico-cortical, rather than subcortically-mediated, auditory-visual pathway (though the precise source(s) of auditory inputs require further scrutiny). Collectively, these neuroimaging data are consistent with a mechanism whereby crossmodal connectivity, ordinarily pruned over the course of development in sighted individuals, is preserved due to early-life visual deprivation, even short-term (corrected early in childhood), and may serve as a scaffolding guiding vision restoration following surgical corrections.

Does the extent of plasticity impact how newly-sighted individuals regain visual functions? This remains to be determined. Until then, some striking insights about the pluripotency of 'visual' occipital cortices come from the research areas of multisensory-processing and sensory-substitution. Evidence across a full palette of neuroimaging methods demonstrates that in healthy, sighted individuals, behaviourally relevant multisensory interactions take place in primary visual cortices [13]. While this pervasiveness of multisensory processes has far-reaching theoretical implications regarding the organisation of perception, its utility has been practically demonstrated through sight restoration via sensory-substitution devices or other approaches, including bionic implants [12]. One family of sensory-substitution devices translates images into so-called 'soundscapes' that individuals learn to use to see [12,14,15]. After a relatively short training of ~30–70 hours, some are able to recognise naturalistic objects, read text/numbers, or even discriminate facial expressions and body postures [12]. Even congenitally blind users can exhibit these skills, achieving acuity above the WHO thresholds for blindness [16]. An organising principle of the brain in general and the visual cortices in particular may thus follow the perceptual function the cortices subserve, rather than the sensory inputs they ordinarily receive [12].

Collectively, the findings of McKyton *et al.* [3], Gandhi *et al.* [5] and Collignon *et al.* [4] provide a wholly new perspective on the nature–nurture debate, enriching also the insights offered by sensory-substitution devices: A given brain region may have a relatively constrained nature with regard to its structure (for example, connections) and function (for example, computations), while simultaneously allowing for the nurturing of these by experience [17]. Unless provided by an altogether novel sensory modality, the ability of these experiences to restore functions lost due to early-life blindness might be substantially limited.

Neurorehabilitation and teaching must incorporate this new perspective. The first of the co-authors of this dispatch has an accent speaking French, despite overall fluency, obvious to any native-speaker, whereas his bilingual children can easily pronounce not only "tree"/"three", but also "un"/"en" and Giverny (/Jzee-VAIR-nie/). Would a curriculum combining current advances in multisensory learning [18] with pharmacological interventions [19] make him sound like a native French-speaker?

REFERENCES

1. WHO factsheet 282 http://www.who.int/mediacentre/factsheets/fs282/en/.
2. Zhao, L., Chen, X.J., Zhu, J., Xi, Y.B., Yang, X., Hu, L.D., Ouyang, H., Patel, S.H., Jin, X., Lin, D., *et al*. (2015). Lanosterol reverses protein aggregation in cataracts. Nature *523*, 607–611.
3. McKyton, A., Ben-Zion, I., Doron, R., and Zohary, E. (2015). The limits of shape recognition following late emergence from blindness. Curr. Biol. *25*, 2373–2378.
4. Collignon, O., Dormal, G., de Heering, A., Lepore, F., Lewis, T.L., and Maurer, D. (2015). Long-lasting crossmodal cortical reorganization triggered by brief postnatal visual deprivation. Curr. Biol. *25*, 2379–2383.
5. Wiesel, T.N., and Hubel, D.H. (1963). Single-cell responses in striate cortex of kittens deprived of vision in one eye. J. Neurophysiol. *26*, 1003–1017.
6. Sur, M., and Leamey, C.A. (2001). Development and plasticity of cortical areas and networks. Nat. Rev. Neurosci. *2*, 251–262.
7. Ostrovsky, Y., Andalma, A., and Sinha, P. (2006). Vision following extended congenital blindness. Psych. Sci. *17*, 1009–1014.
8. Murray, M.M., and Herrmann, C.S. (2013). Illusory contours: a window onto the neurophysiology of constructing perception. Trends Cogn. Sci. *17*, 471–481.
9. Gandhi, T., Kalia, A., Ganesh, S., and Sinha, P. (2015). Immediate susceptibility to visual illusions after sight onset. Curr. Biol. *25*, R358–R359.
10. Hsieh, P.J., Colas, J.T., and Kanwisher, N. (2011). Pop-out without awareness unseen feature singletons capture attention only when top-down attention is available. Psych. Sci. *22*, 1220–1226.
11. Fine, I., Wade, A.R., Brewer, A.A., May, M.G., Goodman, D.F., Boynton, G.M., Wandell, B.A., and MacLeod, D.I.A. (2003). Long-term deprivation affects visual perception and cortex. Nat. Neurosci. *6*, 915–916.
12. Maidenbaum, S., Abboud, S., and Amedi, A. (2014). Sensory substitution: Closing the gap between basic research and widespread

CellPress

practical visual rehabilitation. Neurosci. Biobehav. Rev. *41*, 3–15.

13. Murray, M.M., Thelen, A., Thut, G., Romei, V., Martuzzi, R., and Matusz, P.J. (2015). The multisensory function of primary visual cortex in humans. Neuropsychologia. http://dx.doi.org/10.1016/j.neuropsychologia.2015.08.011.

14. Abboud, S., Hanassy, S., Levy-Tzedek, S., Maidenbaum, S., and Amedi, A. (2014). EyeMusic: Introducing a "visual" colorful experience for the blind using auditory sensory substitution. Restor. Neurol. Neurosci. *32*, 247–257.

15. Meijer, P.B. (1992). An experimental system for auditory image representations. Biomed. Eng. IEEE Trans. *39*, 112–121.

16. Striem-Amit, E., Guendelman, M., and Amedi, A. (2012). Acuity in blind 'Visual' acuity of the congenitally blind using visual-to-auditory sensory substitution. PLoS One *7*, e33136.

17. Hannagan, T., Amedi, A., Cohen, L., Dehaene-Lambertz, G., and Dehaene, S. (2015). Origins of the specialization for letters and numbers in ventral occipitotemporal cortex. Trends Cogn. Sci. *19*, 374–382.

18. Thelen, A., Matusz, P.J., and Murray, M.M. (2014). Multisensory context portends object memory. Curr. Biol. *24*, R734–R735.

19. Iurilli, G., Ghezzi, D., Olcese, U., Lassi, G., Nazzaro, C., Tonini, R., Tucci, V., Benfenati, F., and Medini, P. (2012). Sound-driven synaptic inhibition in primary visual cortex. Neuron *73*, 814–828.

