Recovering stereovision through VR

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Dennis M. Levi
Stereopsis - the impression of three-dimensionality — of objects “popping out in depth” — that most humans get when they view real-world objects with both eyes, based on **binocular disparity** — the differences between the two retinal images of the same world.
Why does stereopsis matter? Binocular viewing
Why does stereopsis matter? Monocular viewing
Binocular/Monocular Peg Placement Time Ratio vs. 1/Stereoacuity

Verghese et al., IOVS, 2016

Binocular faster (< 1)

Binocular slower (> 1)

Poor stereo

Good stereo

$\rho = -0.78$

$p < 0.01**$
Why does stereopsis matter?

**In normal vision**

- Binocular depth thresholds are about a factor of 10 better than monocular thresholds (McKee & Taylor, 2010).

- Visually guided hand movements are significantly impaired when viewing is restricted to one eye. (Fielder & Moseley, 1996; Melmoth & Grant, 2006; O’Connor et al., 2010).

- The binocular advantage is highly correlated with stereoacuity. (Verghese et al., *IOVS*, 2016).
Why does stereopsis matter?

While playing basketball his optic nerve was sheared from the back of his right eyeball.

“Depth perception depends on binocular vision: The brain needs information from both eyes to coordinate where objects are in space. Without depth perception, I often stumble on stairs and curbs, and sudden drop-offs, like sunken living rooms, greet me with a jolt.”
Critical processing stages for normal stereo vision.

1. Both eye’s aligned, functional and reasonably matched.

2. Control over the eye muscles and vergence to bring the images into alignment.

3. Initial matching of retinal images

4. Neural mechanism to combine the images from the two eyes, and compute depth from binocular disparity (and combine it with other depth cues).
Many brain areas are activated by binocular disparity.

Holly Bridge Phil. Trans. R. Soc. B 2016;371:20150254
Stereopsis

- Not everyone experiences stereopsis

- 5 – 20% of the population is estimated to be stereo-blind or stereo-deficient.
Causes of Stereo-blindness and stereo-deficiency

- Parietal cortex damage (Holmes & Horrax, 1919) – percept of a ‘flat world’.

- Right occipito-parietal cortex damage (Schaadt et al., 2015) – deficits in binocular convergence.

- TBI – loss of fusion (Hart, 1969; Miller et al., 1999).

- Agnosia – loss of relative disparity (Read et al., 2010)
Stereopsis

- The most common cause of stereo blindness and stereo deficiency is **amblyopia** and/or strabismus.
Amblyopia is a developmental disorder of vision attributed to a history of abnormal visual experience early in life, during the “sensitive” period.

Amblyopia is an excellent model for studying plasticity.
Amblyopia as a model for studying plasticity

Sensory development and the sensitive period
(Bangarter, 1959)

Is there plasticity beyond the ‘sensitive period’?
“Obstacles” to normal early visual development:

- strabismus
- anisometropia
- form deprivation (e.g., cataract)
Amblyopia:
from the Greek - Amblyos - blunt; opia - sight.

Sometimes called by the misnomer: “lazy eye”

- Amblyopia
  - characterized by:
    - Reduced visual acuity in an otherwise normal eye.
    - Onset early in life (typically before age 6)
    - Associated with a history of abnormal binocular visual experience.
Amblyopia occurs when the two eyes do not get correlated input during a “sensitive period” of development.
Prevalence:

• Amblyopia is a developmental disorder of spatial vision. Prevalence ≈ 3%.

• Strabismus, anisometropia or both occur in about equal proportions (Flom and Neumaier, 1966).
Typically, amblyopia is defined as reduced visual acuity in an otherwise normal eye. However, they have many other deficits including contrast sensitivity and Vernier acuity.
Stereoacuity

Amblyopes often have reduced or absent stereopsis.
Why does stereopsis matter?

**Amblyopic patients:**

- Visuomotor deficits and impaired visual feedback control of movements. (Grant et al., 2007; Melmoth et al., 2009; Niechwiej-Szwedo et al., 2012; Suttle et al., 2011; Wong, 2012).
- Thought to be due to impaired stereopsis, rather than visual acuity loss or impaired vergence control.
- Loss of stereopsis may also result in unstable gait, and for children, difficulties in playing some sports.
- May limit employment opportunities later in life.
Can stereo vision be recovered beyond the ‘sensitive period’?
“A person who has normal binocular vision cannot view the world as a stereoblind individual even when they close one eye. Their brain will use a lifetime of stereovision experiences to fill in the missing stereo information . . . So this brings up a paradox.

A normal binocular viewer cannot imagine vision without stereopsis and a stereoblind viewer cannot imagine vision with stereopsis”.

Question: Can we use rich two-dimensional depth cues as a scaffold for recovering stereopsis in individuals long deprived of 3-D depth perception?

Architectural View:
Francesco di Giorgio Martini (1477)
Question: Can we use other depth cues as a scaffold for recovering stereopsis in individuals long deprived of 3-D depth perception?

- We combine monocular texture cues with stereoscopic cues, where both cues are either consistent or in conflict, and we provide rich information from visual, tactile and kinesthetic feedback.

- Our hypothesis is that if observers can learn the correlations between monocular and disparity cues, they can learn to give greater weight to stereo cues.

Knill & Saunders, 2003
Using VR to train stereo: “Bug squashing”.

Using VR to train stereo: “Bug squashing”.

- Surface slant varied between 20 and 50 deg.
- Motion capture system tracks the slant of the cylinder in real time.
- If the slant of the cylinder matches the slant of the virtual surface (± 5°), the bug explodes.
- Otherwise it scurries away.
Using VR to train stereo: “Bug squashing”.

Movie in slow mo (Knill, 2005)
Dichoptic “bug” alignment, fusion & matching.

Dominant eye

Non-dominant eye

Both eyes
“Bug squashing” increases the hit rate
A simple Bayesian model:

4 parameters:

1) Monocular cue noise.

2) Stereoscopic cue noise.

3) Motor noise.

4) Bias.

- Reduced monocular noise.
- **Huuuge** reduction of stereoscopic noise.
Determining the cue weights.

- **Monocular cues** - stem from distortions of the regular grid pattern mapped onto the surface.

- **Disparity cues** - based on the differences between right and left eyes’ retinal images.

Cues either consistent or inconsistent.

- **Cue weights** derived by regressing the slant of the cylinder against the slant depicted by texture and the slant depicted by disparity:

\[
S_{cyl} = w_{mono} s_{mono} + w_{stereo} s_{stereo} + k
\]

Where \( s_{cyl} \) is the slant of the cylinder; \( s_{mono} \) is the slant suggested by texture cues and \( s_{stereo} \) is the slant suggested by stereo cues.
“Bug squashing” increases the relative weight of stereo cues

\[ RSW = \frac{w_{\text{stereo}}}{w_{\text{stereo}} + w_{\text{mono}}} \]
The evolution of stereo re-weighting:

Strabismic observer, S1
“Bug squashing” changes the weighting of stereo cues (8/11 observers)
“Bug squashing” improves stereoacuity for 6/11 S’s

a. Randot circles

b. Pure Disparity Test
Conclusions:

- Impaired stereopsis may impact visuomotor tasks, playing sports and locomoting safely and may limit career opportunities.

- Reduced stereopsis is the most common deficit associated with amblyopia under ordinary (binocular) viewing conditions.

- Recovery of at least some degree of stereopsis in patients with long-standing impairment of binocular vision is possible using virtual reality, even beyond the critical period.

- Recovery is accomplished by upweighting reliance on stereoscopic cues, and may be accompanied by significant improvements in stereoacuity.

- The principles outlined here maybe applied to a wide range of visual impairments.
In the beginning: The synoptophore
In the beginning:

Virtual Reality

(Sutherland, 1968)
The future is here:
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“Bug squashing” reduces suppression

Pre-training contrast ratio (weak/strong)

Anisometropic
Post FU
A1
A2

Strabismic
S1
S2
S3
S4

Mixed
M1
M2
M3
M4
M5

Controls (N=3)
“Bug squashing” improves visual acuity for some.