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Cortex – Research Report

Title

Neuroplasticity in older adults revealed by temporary occlusion of one eye

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Declarations of interest

None

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Highlights

1. Temporarily depriving one eye of visual experience reveals adult neuroplasticity
2. Two hours of monocular deprivation alters ocular dominance in healthy older adults
3. Neuroplasticity of visual cortex is preserved and possibly strengthened in healthy older adults

Abstract

Occluding one eye for several hours alters visual experience. Specifically, occluding one eye shifts the balance of ocular dominance to favour the recently deprived eye, which can be measured using binocular rivalry. This ocular dominance shift demonstrates homeostatic neuroplasticity within the visual system and has been explored in detail in younger adults. Here we measure whether the strength and general features of neuroplasticity revealed by monocular patching are maintained in older adults. Thirty younger (18-35 years) and 30 older adults (60-81 years) participated. Binocular rivalry features were measured before and after 2 hours of occlusion. Post-patching, perceptual dominance of the non-patched eye decreased ($p<0.001$) in both age groups. The effect of occlusion on all features of binocular rivalry did not significantly differ between groups. The older visual system maintains the ability to rapidly adjust to changes in perceptual experience induced by eye occlusion. This preservation of neuroplasticity suggests that visual training methods designed to improve visual performance based on eye occlusion should maintain effectiveness into older age.

Keywords (max 5 words)

Short-term monocular deprivation, ocular dominance, neuroplasticity, visual cortex, ageing

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1. Introduction

There has been considerable recent interest in the ability of short-term monocular deprivation to alter visual experience in adults, as a means of exploring neuroplasticity within the adult visual system (Baldwin & Hess, 2018; Lunghi, Burr, & Morrone, 2011; Lunghi, Burr, & Morrone, 2013; Lunghi & Sale, 2015; Zhou, Clavagnier, & Hess, 2013). The general, and highly replicated, observation is that when ocular dominance is measured before and after short-term monocular deprivation (by patching one eye), there is a shift in ocular dominance to favour the recently deprived eye. Ocular dominance describes the preference of input from one eye over the other. Many prior experiments have used the following approach: occlude one eye with a patch for a duration of around two hours, then measure the temporary shift in ocular dominance after patch removal. The shift in ocular dominance is maximal immediately post-patch removal but has been shown to last for several hours (Lunghi et al., 2011; Lunghi et al., 2013). The most common method used in these patching experiments to determine the balance in dominance between the two eyes is binocular rivalry. Binocular rivalry involves presenting the two eyes with different but similarly salient stimuli, which then compete for perceptual dominance. The result is regular switching between the perceptual dominance and suppression of the competing stimuli. After temporary occlusion, the stimulus presented to the recently patched eye dominates perception, with the strength of this effect used as an index of short-term homeostatic neuroplasticity (Zhou, Baker, Simard, Saint-Amour, & Hess, 2015; Zhou et al., 2013).

Physiologically, prior evidence from magnetic resonance spectroscopy (MRS) suggests that temporary occlusion decreases resting state GABA concentration in visual cortex, with the amount of GABA reduction being correlated with the magnitude of effect of deprivation

on the rivalry task (Lunghi, Emir, Morrone, & Bridge, 2015). Cholinergic mechanisms have also been implicated, with a recent study demonstrating that the ingestion of donepezil (a cholinesterase inhibitor) reduces the magnitude and duration of the ocular dominance shift following temporary occlusion (Sheynin, Chamoun, et al., 2019). Consequently, short-term plasticity might be phenomenologically altered in individuals with conditions that impact on the regulation of either cholinergic or GABA-ergic systems. We propose that one such situation is healthy human aging. Indeed, the presence or absence of visual system neuroplasticity in older adults has potentially important implications for the ability to adapt to changes in visual status with age and disease, and may influence the choice of future clinical approaches designed to enhance visual performance through training.

The precise visual neural circuitry underlying the effects of temporary occlusion on eye dominance is still being uncovered (for example see: Bai, Dong, He, & Bao, 2017; Baldwin & Hess, 2018; Binda et al., 2018; Ramamurthy & Blaser, 2018; Wang, Yao, He, Zhou, & Hess, 2017). It is generally accepted that patching influences inter-ocular contrast gain control mechanisms (Zhou et al., 2015; Zhou et al., 2013) such that localised changes in the balance between activation and inhibition allow up/down regulation of selected neural signals. The resulting effect is reduced inhibition of the signal from the deprived eye after the patch is removed. To date, all reports investigating this phenomenon have tested younger adults. However, other visual processes that are reliant on contrast gain control mechanisms can be markedly altered in the older visual system. Examples include: differences in contrast adaptation properties to chromatic stimuli (Elliott, Werner, & Webster, 2012), differences in contrast gain (Elliott & Werner, 2010), and strengthening of perceptual spatial surround effects involving contrast judgements (for review see: McKendrick, Chan, & Nguyen, 2018). The balance of evidence from this broad range of visual perceptual studies suggests a

strengthening of contrast gain control mechanisms in the aging visual system. Further evidence for this proposition comes from neurophysiological study of aged cat primary visual cortex that demonstrates significantly stronger contrast adaptation in some visual cortical cells relative to those found than in younger animals (Hua, Li, Tang, Wang, & Chang, 2009). Taken together, these findings suggest that the effects of temporary occlusion of one eye might actually be strengthened in older adults.

An additional physiological factor that suggests that older adults might have an altered neuroplastic experience post-occlusion arises from the study of GABA concentrations in visual cortex (Pitchaimuthu et al., 2017). Previous study of temporary monocular occlusion in younger adults implicated visual cortical modulation of GABA levels as key to the strength of neuroplastic effects demonstrated within individuals (Lunghi et al., 2015). While GABA-ergic inhibition within visual cortex in older adults is often assumed to be reduced based on inferences from single-cell neurophysiology in senescent primates (Leventhal, Wang, Pu, Zhou, & Ma, 2003), direct evidence for reduced GABA-ergic inhibition in humans is lacking. Indeed, a recent human MRS study actually revealed elevated GABA concentrations in visual cortex in older adults (Pitchaimuthu et al., 2017). Of further relevance was the observation that increased GABA levels correlated with slower binocular rivalry (Pitchaimuthu et al., 2017), consistent with the idea that rivalry switch rate is dependent, at least in part, on levels of cortical inhibitory neurotransmitter. While it is not immediately apparent how this cross-sectional observation may relate to the ability for resting state GABA levels to change under conditions of monocular deprivation, the presence of dysregulation of the GABA-ergic system in older adults adds further support to the possibility of increased perceptual biasing in the response to temporary occlusion.

Here we explore whether the strength and general features of neuroplasticity revealed by two hours of monocular patching is maintained in older adults. Specifically, we investigated binocular rivalry outcome measures that provide insight into the balance between excitation and inhibition in visual cortex. Mutual inhibition is considered critical for the alternation between two exclusive-dominance percepts (Blake, 1989; Blake & Logothetis, 2002; Klink, Brascamp, Blake, & van Wezel, 2010; Said & Heeger, 2013; Tong, Meng, & Blake, 2006), while pharmacological agonism of specific GABA-ergic inhibitory receptors has recently been linked to the prominence of mixed percept (Mentch, Spiegel, Ricciardi, & Robertson, 2019). Furthermore, the initial period of dominance before the first binocular rivalry switch (or 'onset rivalry'), which has previously been unexplored in the context of short-term monocular deprivation paradigms, is also considered to depend critically on inhibition (akin to other forms of visual suppression or masking, see review by Stanley, Forte, Cavanagh, & Carter, 2011). We show that the older visual system maintains the neuroplastic ability to respond to short term changes in visual experience. The preservation of neuroplasticity suggests that visual training methods designed to improve visual performance based on eye occlusion (Lunghi, Sframeli, et al., 2019; Sauvan et al., 2019) should maintain effectiveness into older age.

2. Material and methods

The study was approved by the University of Melbourne Human Research Ethics Committee (#1851069) according to a protocol consistent with the Declaration of Helsinki. We report how we determined our sample size, all data exclusions, all inclusion/exclusion

criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study below.

2.1. Participants

We performed a power analysis based on the effect size (0.73) of patching on ocular dominance reported by previous work (Lunghi & Sale, 2015) and a two-tailed difference between matched pairs in G*Power (Faul, Erdfelder, Lang, & Buchner, 2007). Twenty-seven participants would be required in each group to achieve a power of 0.95 at a significance level of 0.05. Accordingly, thirty younger (aged 18-35 years; mean age, 25 years) and 30 older adults (aged 60-81 years; mean age, 68 years) were recruited via advertisements within the University, on community noticeboards and from a database of previous research participants. Written consent was obtained from participants prior to testing and participants received a $20 gift voucher to contribute to any out-of-pocket travel expenses.

The single testing session was 4 hours duration including a vision and ocular health screening. The following inclusion/exclusion criteria were established prior to data analysis: All participants had distance best corrected visual acuity equal or better than 6/7.5 in each eye with corrective lenses of less than ±5 D sphere and less than 2 D astigmatism. Ocular health was screened using slit lamp biomicroscopy and ophthalmoscopy to ensure absence of ocular pathology. All participants had a cataract grading of less than 1.5 according to the Lens Opacities Classification System III (LOCS III) (Chylack et al., 1993).

2.2. Experimental procedure

Figure 1 is a schematic of the experimental procedure, including a depiction of the binocular rivalry test stimuli and procedure. Participants were trained on the binocular

rivalry task and completed at least one practice run before commencing the actual trials. Binocular rivalry was measured at baseline prior to two hours of monocular deprivation by patching, followed by post-patching binocular rivalry tests at 0, 3, 6, 9, 12, 15, 30, 45, 60 and 90 minutes after patch removal. To investigate the effect of short-term monocular deprivation, we compared baseline rivalry data (sum of 3-4 baseline trials) to the data collated in the period 0-9 minutes immediately after patching (sum of 3 trials, one trial each at 0, 3 and 6 minutes) and 9-18 minutes after patching (sum of 3 trials, one trial each at 9, 12 and 15 minutes). We also collected data at later timepoints (one trial each at 30, 45, 60 and 90 minutes) to demonstrate the longevity of the effect of temporary occlusion. Between each trial, participants were given a short (~20 s) break.

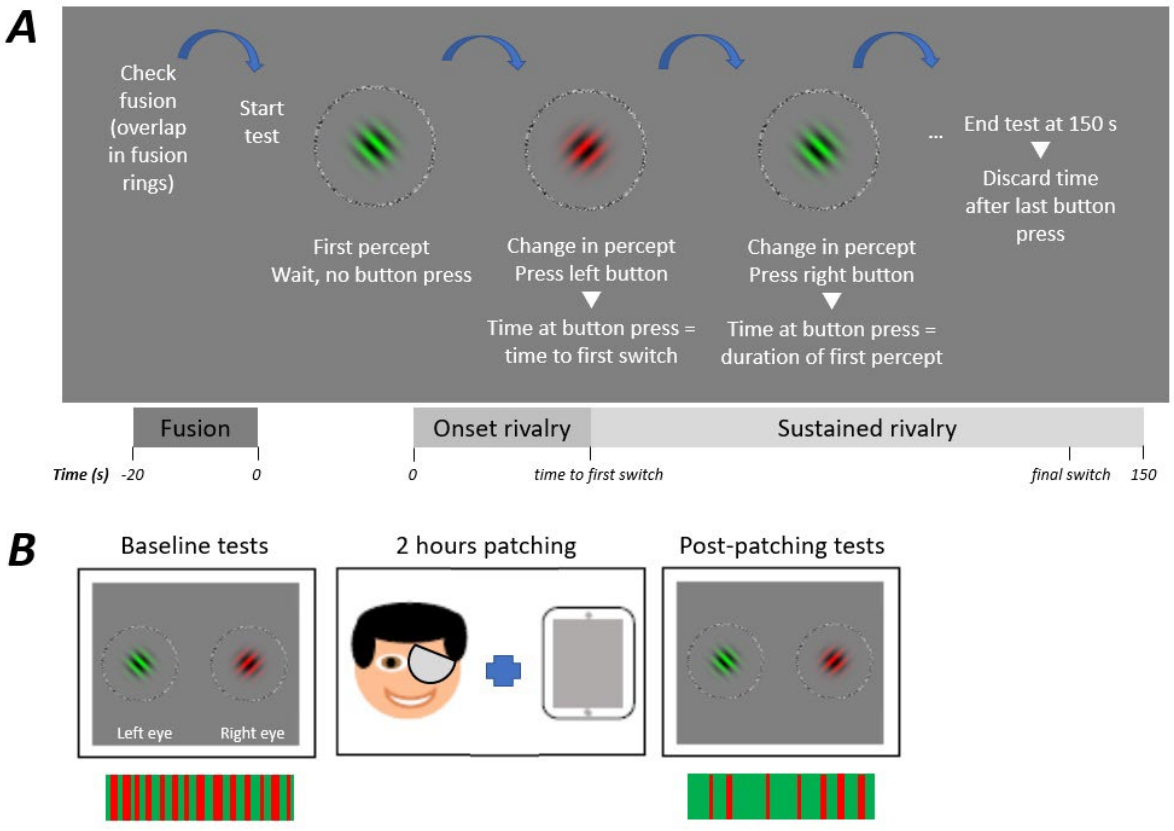


Figure 1 (colour print). Schematic of the visual perceptual testing. *(A) Schematic of a single binocular rivalry trial. The trial started when the participant confirmed fusion. The trial ran for 150 seconds. Time to first switch was taken as the measure of onset rivalry. During the subsequent period of sustained rivalry, percept duration for red, green, and mixed percepts was recorded. The time after the last button press was discarded for analysis. (B) Schematic of the test session. Baseline binocular rivalry tests were conducted, followed by two hours of monocular deprivation with a translucent patch over the dominant eye and normal visual tasks (including watching a movie and/or computer work). After patch removal, binocular rivalry was tested at 0, 3, 6, 9, 12, 15, 30, 45, 60 and 90 minutes (one trial at each timepoint). Under each panel, we include an idealised example of perceptual switches between the dominant and non-dominant exclusive percepts (red stimulus seen by right eye, green stimulus seen by left eye) that typically occur randomly at baseline. After patching, the deprived eye (in this case, left eye patched) is typically reported to become more dominant (more green percepts).*

2.3. Binocular rivalry

The visual stimuli for the binocular rivalry task were presented using software (https://melbourne.figshare.com/articles/software/_/14368988) written in PsychoPy Version 3.0 and presented on an LCD monitor (BenQ ZOWIE XL2430-B, Taoyuan City, Taiwan) with a refresh rate of 100 Hz and a screen resolution of 1920 x 1080 pixels. The stimuli were dichoptically presented using a stereoscope (ScreenScope, Stereo Aids, Albany, Australia) and the response was collected via mouse press. Participants were seated comfortably at a

chinrest and wore the appropriate refractive correction for the working distance (60 cm). All participants were naïve to the experimental purpose.

A schematic of a single binocular rivalry trial (150 second duration) is shown in Figure 1. A red and green circularly windowed sinusoidal grating pattern (diameter=2°, spatial frequency= 4 cyc/deg), oriented at 45° and 135°, were presented to the left and right eyes, respectively. The stimuli presented to each eye remained consistent throughout the experiment. Two surrounding circles of 12° diameter (width = 0.3°) constructed of random black and white dots with zero disparity were present throughout testing to aid fusion. At the beginning of each trial, a central vertical line (left, length = 0.5°) and a central horizontal line (right, length= 0.5°) were used to indicate the target location and ensure that the participant could see a binocularly fused fixation cross. The binocular rivalry trial started as soon as the participant indicated fusion, at which point the fixation cross disappeared but the fusion circles remained throughout the trial. Participants were instructed not to press a button until the first switch in percept (time to first switch). Participants then indicated subsequent changes in percept by clicking a mouse button (right button if the percept was predominantly red or left button if the percept was predominantly green). Otherwise, if the percept was a combination of red and green (either piecemeal or superimposed) where neither red nor green dominated, participants were instructed to press the middle button to indicate mixed percept. Duration of each percept (time between switches) was recorded.

2.4. Monocular deprivation

The dominant eye was determined using a clinical test of sighting dominance (i.e. which eye dominated when a distant target was viewed binocularly) and was occluded for two

hours. Two layers of translucent adhesive tape (3M Transpore surgical tape, Maplewood, Minnesota, USA) was fixed to a Halberg trial lens clip over a participant's own spectacles, or attached to a customised eye patch (BSN Medical Leukofix transparent tape, Mulgrave, Victoria, Australia) if the participant did not wear spectacles. The translucent tape degraded form perception but allowed light to reach the retina (approximately 30% light attenuation). Participants were advised to sit quietly during the two hours of patching and were free to perform normal activities in standard room lighting such as working on a computer, watching a movie on an iPad and having food and beverages, with the exception of caffeine intake, which was avoided due to cholinergic alteration of perceptual eye dominance plasticity (Sheynin, Chamoun, et al., 2019) and the potential for caffeine to increase brain acetylcholine levels (Carter, O'Connor, Carter, & Ungerstedt, 1995; Corradetti, Pedata, Pepeu, & Vannucchi, 1986).

2.5. Data analysis

Our outcome measures of interest are presented herein in the sequential order by which binocular rivalry characteristics are extracted, starting with time to first switch (as a measure of onset rivalry), sustained rivalry switch rate (ratio of the number of perceptual switches to total sustained rivalry time), and proportion of total sustained rivalry time spent in the dominant eye, non-dominant eye and mixed percepts. Time to first switch and time after final switch (Figure 1A) were deducted from 150 seconds (length of trial) to obtain total sustained rivalry time. Although we recorded all percept durations for each of the dominant eye, non-dominant eye and mixed percepts, binocular rivalry percept duration distributions are typically a gamma distribution (Levelt, 1967) hence calculating median

percept duration is a limited descriptor of the data. Nevertheless, we present median percept duration data in Supplementary Material A for comparison to other published reports. Our analysis concentrates on the timepoints immediately after patch removal (0-9 minutes), and on the final measured timepoint (90 minutes post patch removal). Data for all timepoints is provided in Supplementary Material A.

Statistical tests were predominantly conducted in SPSS version 25.0 (IBM, Armonk, NY, USA). Data were tested for normality using a Kolmogorov-Smirnov test (see Supplementary Material A). Between-group comparisons of normally distributed data (switch rate, proportion of time spent in deprived and non-deprived eye percepts) were conducted using independent student t-tests (paired and unpaired, where appropriate) and repeated measures analysis of variance (RM-ANOVA). A Huynh-Feldt correction was applied for data that did not satisfy Mauchly's test of sphericity. For non-normally distributed data (time to first switch, proportion of time spent in mixed percept), between-group comparisons were conducted using Mann-Whitney rank sum tests, paired non-parametric Wilcoxon signed rank tests to compare across two timepoints within groups, and Friedman non-parametric tests to compare across several timepoints within groups. A *p* value of 0.05 was set as the criterion for statistical significance. Effect sizes (eta-squared, or partial eta-squared values) and Bayes factors are provided. Bayes factors were determined using JASP (JASP Team, 2020). In addition, in order to demonstrate the effect of deprivation, we normalised the binocular rivalry outcome measures to each individual's baseline and compared these normalised values between the groups.

2.6 Preregistration

No part of the study procedures nor study analysis were preregistered prior to the research being conducted.

3. Results

3.1. Onset of rivalry at baseline and after temporary occlusion

Figure 2 shows the time to first switch (i.e. onset of rivalry) in the younger and older groups at baseline and after temporary occlusion. At baseline, time to first switch was delayed in the older group by, on average, ~750ms relative to the younger group (median ± IQR: younger 2.30 ± 1.16 seconds, older 3.06 ± 2.56 seconds; Mann-Whitney rank sum test: $p=0.003$, $\eta^2 = 0.15$). It is worth noting that this difference between age-groups is substantively larger than predicted by age-related differences in choice-reaction times which are slowed by approximately 20ms per decade (Woods, Wyma, Yund, Herron, & Reed, 2015). Immediately after occlusion (i.e. comparing baseline to 0-9 minutes immediately after patching), time to first switch increased in the older group (Figure 2D; Wilcoxon paired signed rank test: $p=0.032$, partial $\eta^2 = 0.15$) but not in the younger group (Figure 2C; Wilcoxon paired signed rank test: $p=0.77$, partial $\eta^2 = 0.003$). This age-related delay in time to first switch remained at the 90 min timepoint (Figure 2B; Wilcoxon paired signed rank test: $p=0.079$, partial $\eta^2 = 0.10$), suggesting a prolonged effect of short-term monocular deprivation in older adults.

To directly compare the effect of deprivation on onset rivalry between groups, we normalised the time to first switch at 0-9 minutes after patch removal to baseline for each individual. A larger positive value on the y-axis (Figure 2E) indicates a delayed time to first switch after deprivation relative to baseline. Although some older adults show a substantial

311 delay in time to first switch immediately after patching (see outliers in Figure 2E), there was
312 no between-group difference in normalised time to first switch at 0-9 minutes (Mann-
313 Whitney rank sum test, $p=0.08$, $\eta^2 = 0.052$). Bayes factor analysis suggested anecdotal
314 evidence for the null hypothesis ($BF_{01} = 1.20$).

315 We also investigated the nature of the immediate percept after patch removal (i.e.
316 whether from the deprived or non-deprived eye). At the first timepoint after deprivation,
317 older adults showed relatively more deprived eye percepts (63% dominant/deprived eye,
318 37% non-dominant eye) than the younger group (30% dominant/deprived eye, 70% non-
319 dominant eye; chi-square test of proportions: $\chi^2=6.70$, $p=0.010$). This was not the case at
320 baseline, where the proportion of dominant and non-dominant percepts at onset was the
321 same for both younger and older groups (47% dominant eye, 53% non-dominant eye).

322

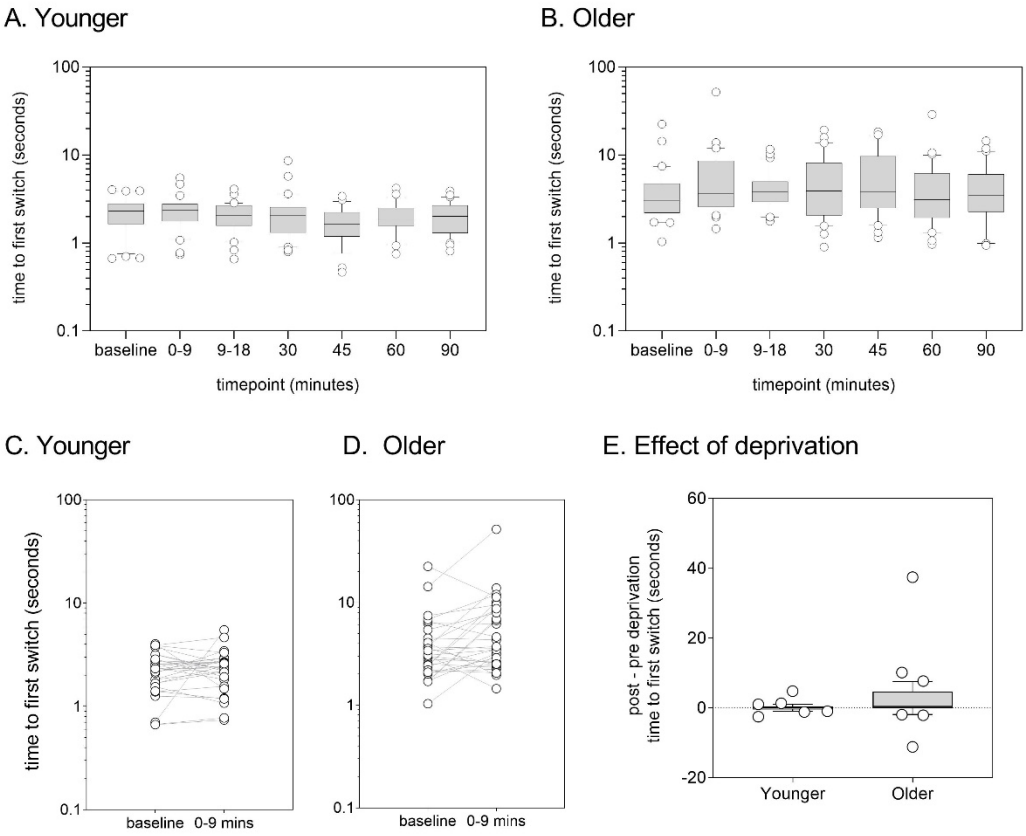
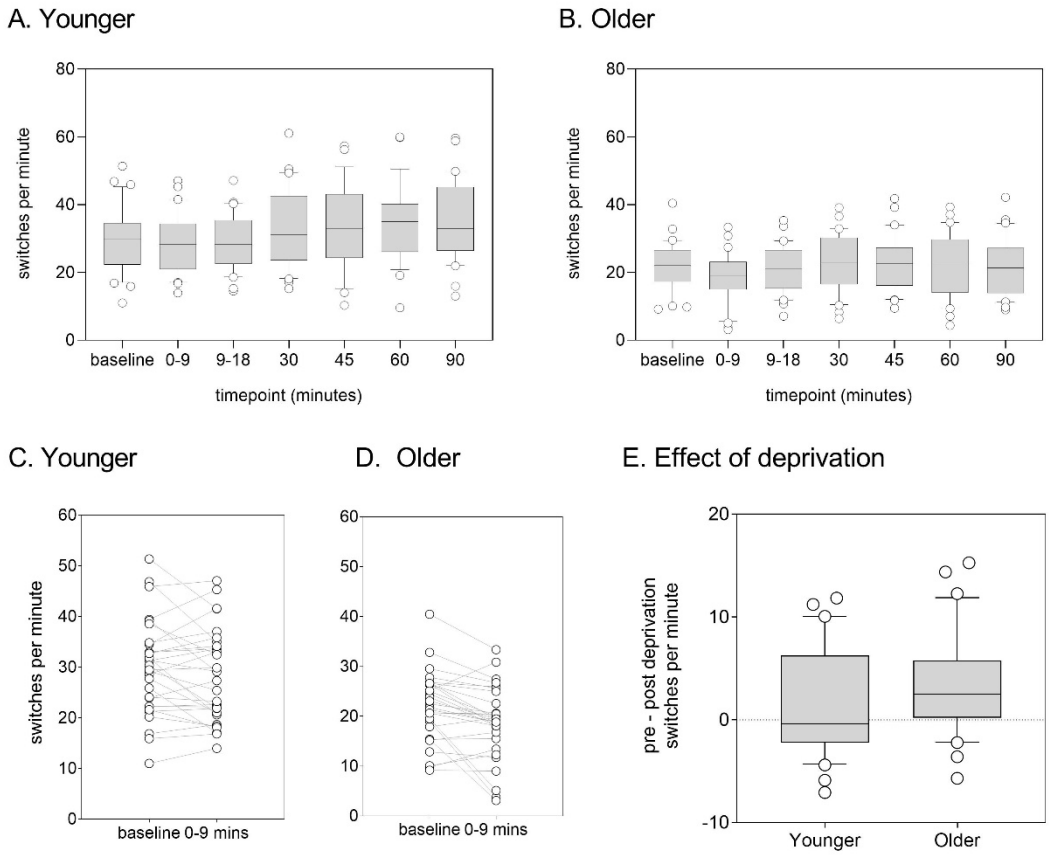


Figure 2. Onset of rivalry (time to first switch). *Time to first switch is shown at all timepoints for the (A) younger adults and (B) older adults. Before-after plots show the paired comparisons between baseline vs 0-9 minutes only for the (C) younger adults and (D) older adults. (E) Effect of deprivation (difference between time to first switch measured before and after monocular deprivation), at 0-9 minutes immediately after patch removal. A higher positive value on the y-axis indicates a relatively delayed time to first switch after deprivation compared to baseline. Boxes depict the median, 25th and 75th percentiles, with the whiskers showing the 10th and 90th percentiles. All outliers are shown as individual symbols.*

3.2 Sustained rivalry switch rate at baseline and after temporary occlusion

335 At baseline, older adults showed slower sustained rivalry switching compared to
336 younger adults (t_{58}=3.73, p<0.001, η^2 = 0.19), consistent with previous reports (Abuleil,
337 McCulloch, & Thompson, 2019; Pitchaimuthu et al., 2017). The age-related difference in
338 switch rate was also present after patching (Figure 3; RM-ANOVA main effect of group:
339 F(1,58)=18.9, p<0.001, partial η^2 = 0.25). Both groups showed a similar reduction in switch
340 rate 0-9 mins immediately after temporary occlusion (RM-ANOVA main effect of patching:
341 F(1,58)=13.6, p=0.001, partial η^2 = 0.19; group x patching interaction: F(1,58)=1.70, p=0.20,
342 partial η^2 = 0.03), suggesting no age-related difference in the effect of short-term monocular
343 deprivation on switch rate. This result is further supported by directly comparing the switch
344 rate normalised to baseline (Figure 3E; Mann-Whitney rank sum test, p=0.10, η^2 = 0.046). A
345 larger positive value on the y-axis (Figure 3E) indicates slower sustained rivalry switch rate
346 after deprivation relative to baseline. The Bayes factor for the data in Figure 3E was 1.24
347 (BF_{01}), providing anecdotal support for the null hypothesis (that the effect of deprivation on
348 switch rate is equivalent between groups).

349 To consider the longevity of the effect of patching on switch rate, we compared data
350 from 0-9 mins to 90 mins post-patching. Both groups showed an increase in switch rate at
351 90 mins post-patching (RM-ANOVA main effect of time post-patching: F(1,58)=35.7,
352 p<0.001, partial η^2 = 0.38; group x time post-patching interaction: F(1,58)=3.79, p=0.056,
353 partial η^2 = 0.06), suggesting a recovery in the number of switches over time in younger and
354 older adults.



355

356 ***Figure 3. Sustained rivalry switch rate (switches per minute).*** *Switch rate is shown at all*
357 *timepoints for the (A) younger adults and (B) older adults. Before-after plots show the paired*
358 *comparisons between baseline vs 0-9 minutes only for the (C) younger adults and (D) older*
359 *adults. (E) Effect of deprivation (difference between switch rate measured before and after*
360 *monocular deprivation), at 0-9 minutes immediately after patch removal. A higher positive*
361 *value on the y-axis indicates a relatively slower switch rate after deprivation compared to*
362 *baseline. Boxes depict the median, 25th and 75th percentiles, with the whiskers showing the*
363 *10th and 90th percentiles. All outliers are shown as individual symbols.*

364

365 *3.3. Time spent in exclusive dominance and mixed percepts after temporary occlusion*

Figure 4 summarises the percentage of time spent in the deprived (or dominant) eye, non-deprived (or non-dominant) eye and mixed percepts before and after patching. Time spent in the dominant eye percept tended to increase in the 0-9 mins after the patch was removed (white symbols in Figures 4A and 4B; RM-ANOVA main effect of patching: $F(1,58)=3.71$, $p=0.059$, partial $\eta^2 = 0.06$). However, there was no group difference (RM-ANOVA main effect of group: $F(1,58)=2.00$, $p=0.16$, partial $\eta^2 = 0.03$; group x patching interaction: $F(1,58)=0.002$, $p=0.97$, partial $\eta^2 < 0.001$), indicating that both older and younger adults showed similar effects of short-term monocular deprivation on the dominant eye percept. In both groups, the dominant eye percept returned to baseline dominance at 90 mins post-patching (RM-ANOVA main effect of time post-patching: $F(1,58)=4.53$, $p=0.038$, partial $\eta^2 = 0.07$; group x time post-patching interaction: $F(1,58)=0.10$, $p=0.75$, partial $\eta^2 = 0.002$).

On the other hand, time spent in the non-dominant eye percept decreased immediately following patching (green symbols in Figures 4A and 4B; main effect of patching: $F(1,58)=29.6$, $p<0.001$, partial $\eta^2 = 0.34$) in both groups (main effect of group: $F(1,58)=0.21$, $p=0.65$, partial $\eta^2 = 0.004$; group x patching interaction: $F(1,58)=0.64$, $p=0.43$, partial $\eta^2 = 0.01$). At 90 mins post-patching, the time spent seeing the non-dominant eye percept increased in both groups (RM-ANOVA main effect of time post-patching: $F(1,58)=7.99$, $p=0.006$, partial $\eta^2 = 0.12$; group x time post-patching interaction: $F(1,58)=0.53$, $p=0.47$, partial $\eta^2 = 0.009$). Overall, our results are consistent with a shift in ocular dominance towards the dominant eye after short-term monocular deprivation, in both younger and older groups, which did not persist at 90 minutes after the patch was removed.

A possible interpretation of our ocular dominance data is that the increase in time spent in the dominant eye percept compensated entirely for the reduction in time spent in the non-dominant eye percept following patching. However, this interpretation does not consider the time spent in mixed percept. Ageing did not affect baseline levels of mixed percept (Mann-Whitney rank sum test, p=0.96, $\eta^2 < 0.001$). Patching significantly increased the time spent in mixed percept in younger adults (Figure 4C; Wilcoxon paired signed rank test: p=0.007, partial $\eta^2 = 0.24$), which returned to baseline levels at 90 mins after patch removal (Wilcoxon paired signed rank test: p=0.022, partial $\eta^2 = 0.18$). The same increase was seen in mixed percept after short-term monocular deprivation in the older adults (Figure 4D; Wilcoxon paired signed rank test: p=0.044, partial $\eta^2 = 0.13$). However, the effect did not return to baseline and rather persisted at 90 minutes post-patching (Wilcoxon paired signed rank test: p=0.66, partial $\eta^2 = 0.007$) in the older adults.

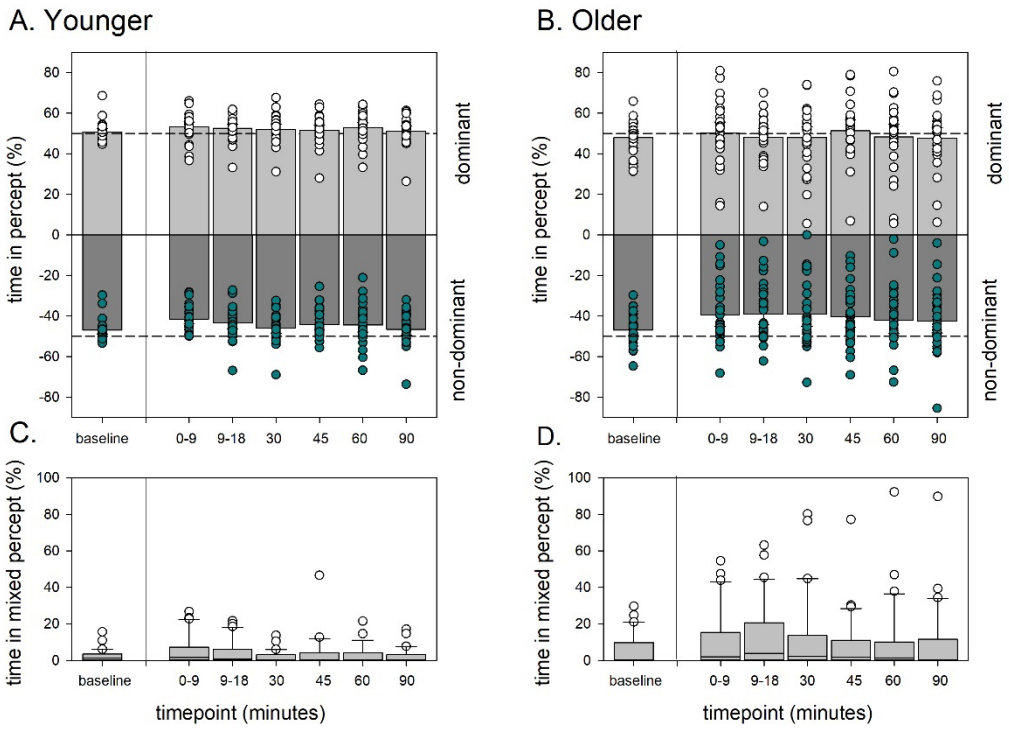


Figure 4 (colour print). Time spent in each percept (%) at baseline and after short-term monocular deprivation (0-9, 9-18, 30, 45, 60, 90 minutes after patch removal) in the younger and older groups. *(A) Time spent seeing the dominant and non-dominant eye percept for the younger group (n=30). The bars indicate the group mean, and the symbols represent individual results. Horizontal dashed lines at 50% demonstrate that at baseline, the average % time spent in the dominant eye percept is just above 50%, and the average % time spent in the non-dominant eye percept is below 50%. (B) Time spent seeing the dominant and non-dominant eye percept for the older group (n=30). (C) and (D) show boxplots of the time spent in mixed percept for the younger and older groups, respectively. Boxes depict the median, 25th and 75th percentiles, with the whiskers showing the 10th and 90th percentiles. All outliers are shown as individual symbols.*

To compare the effect of monocular deprivation on exclusive dominance percepts between groups, we first calculated an index of ocular dominance (Equation 1) as per previous work (Lunghi, Daniele, et al., 2019), and subtracted the pre-deprivation ocular dominance index from the post-deprivation ocular dominance index. In equation 1, T refers to time, spent in the deprived (Dep) and non-deprived (NonDep) eyes.

$$\frac{T_{Dep}}{T_{Dep}+T_{NonDep}} \qquad \text{(Equation 1)}$$

Complete dominance of the deprived eye is indicated by an ocular dominance index of 1; therefore, a smaller difference in ocular dominance on the y-axis (Figure 5A) implies a weaker effect of deprivation. At 0-9 minutes immediately after patch removal, although both groups showed a consistent bias towards the deprived (or dominant) eye percept,

there was no difference between older and younger adults in the strength of the effect of deprivation on ocular dominance (Figure 5A; Mann-Whitney rank sum test, p=0.84, $\eta^2 <$ 0.001). The Bayes factor for this analysis is 3.55 (BF_{01}) suggesting moderate evidence for the null hypothesis. Similarly, when comparing the proportion of mixed percept before and after deprivation between groups, older and younger adults did not differ in the effect of deprivation at 0-9 minutes (Figure 5B; Mann-Whitney rank sum test, p=0.95, $\eta^2 < 0.001$, BF_{01} = 3.66). At 90 minutes post-deprivation (Figures 5C and 5D), neither ocular dominance (Mann-Whitney rank sum test, p=0.32, $\eta^2 = 0.017$, $BF_{01} = 2.10$) nor mixed percept (Mann-Whitney rank sum test, p=0.13, $\eta^2 =0.038$, $BF_{01} = 1.69$) showed significant group differences when normalised to baseline. Thus we find no evidence for a difference in neuroplasticity effects on exclusive dominance and mixed percepts with ageing.

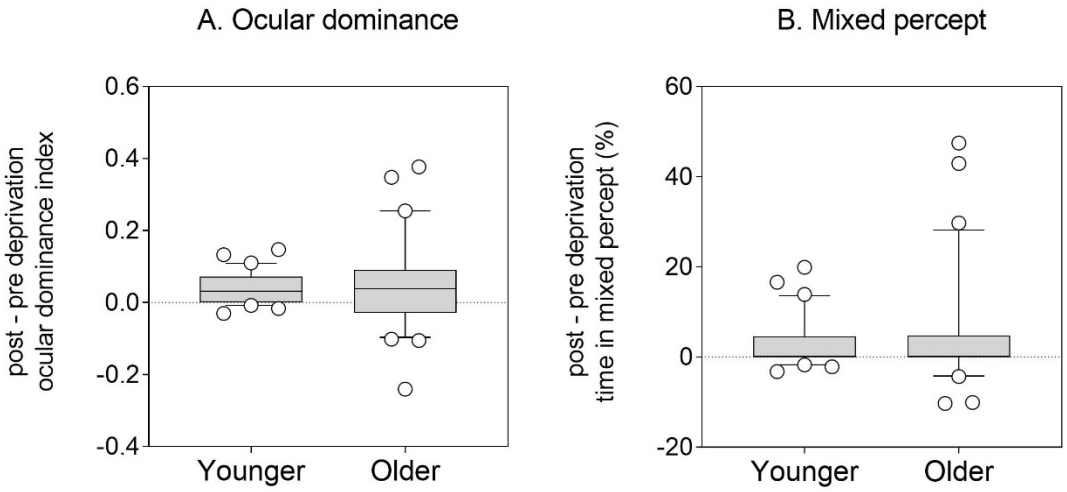


Figure 5. Effect of deprivation (difference between outcomes measured before and after monocular deprivation) on ocular dominance and mixed percept. *Immediate effect of deprivation at 0-9 minutes on (A) ocular dominance index, calculated as per Equation 1*

based on proportion of total time spent in the deprived (or dominant) and non-deprived (or non-dominant) eye percepts, and on (B) proportion of total time spent in mixed percept. Boxes depict the median, 25th and 75th percentiles, with the whiskers showing the 10th and 90th percentiles. All outliers are shown as individual symbols. Smaller values on the y-axis indicate a weaker effect of deprivation.

4. Discussion

Our data demonstrates that the older adult visual system is still highly capable of short-term neuroplastic regulation of visual experience. The ability of a short period (2 hours) of monocular translucent occlusion to alter binocular rivalry dynamics is similar in older and younger adults, despite age-related differences in rivalry characteristics in the absence of occlusion (i.e. slower rivalry switching and longer time to the first switch in older adults).

Based on previous literature suggesting a strengthening of some forms of contrast gain regulation effects in older adults (Elliott & Werner, 2010; Elliott et al., 2012; McKendrick et al., 2018), we hypothesised that the effects of short-term deprivation might be strengthened in older adults. Our data did not provide evidence in support of this outcome. Specifically, the standard metric of homeostatic neuroplasticity (ocular dominance index, Figure 5A) was not different between groups. Interpretation of the Bayes factor suggests moderate evidence in support of the null hypothesis in this case. However, it is worth noting that we observed substantial inter-individual differences in the effect of occlusion, particularly in the older adult group.

Further work is required to explore the likely mechanisms underpinning inter-individual differences in various aspects of binocular rivalry, however, there is recent data that

points to interesting relationships between mechanisms underpinning different types of inhibitory phenomena in human vision. Of particular relevance is a recent observation that interindividual differences in tilt illusion strength (an alternate measure of inhibition within the visual system) partially predicts the magnitude of effect of occlusion on ocular dominance in younger adults, such that a stronger tilt illusion predicts a stronger effect of occlusion (Steinwurzel, Animali, Cicchini, Morrone, & Binda, 2020). We have previously shown that the tilt illusion strength is, on average, elevated in older adults (Nguyen & McKendrick, 2016). However substantial interindividual differences in performance existed in that dataset also. One interpretation of the finding of Steinwurzel et al (2020), is that older adults with stronger tilt illusion strength, which is associated with stronger visual cortical inhibition (Seymour, Stein, Clifford & Sterzer 2018), should be predicted to have slower binocular rivalry switch rates, and in turn, a stronger effect of occlusion on the ocular dominance index. Clearly we do not have data on the strength of the tilt illusion in our participants. However, we did check whether there was any evidence in our data for a relationship between baseline rivalry switch rate and the effect of occlusion on ocular dominance. There was not (Kendall's tau = 0.054, p=0.54, BF_{01} = 4.9). We also considered whether ocular dominance plasticity is related to the proportion of mixed percept at baseline (Kendall's tau = -0.03, p = 0.74, BF_{01} = 5.6). Consequently, in our dataset, we did not find evidence to support a relationship between baseline features of rivalry and the strength of the effect of occlusion.

At the time of experimental design, we were primarily interested in the measurement of exclusive visual percepts (entirely red or entirely green) because the majority of previous literature exploring the effects of short-term monocular deprivation on binocular rivalry dynamics has concentrated on the analysis of exclusive percepts. We did ask participants to

report the presence of mixed percept (a mix of red and green) but did not explore in detail the specific phenomenology of the mixed percept experience. Mixed percepts can have varied forms but are typically either superimposed versions of the two component gratings or piecemeal representations. It has recently been reported that short-term monocular occlusion results in an increase in mixed percept, and specifically, an increase of superimposition (Sheynin, Proulx, & Hess, 2019); although an increase of mixed percept post occlusion is not universal (Steinwurzel et al., 2020). Consistent with the general findings of Sheynin et al (2019), our Figure 4 shows a trend for a decrease in the time spent in the non-dominant eye post-patching with some reallocation of that time to mixed percept. This effect occurred in both younger and older adults. While the mechanisms underlying mixed percept are a matter of considerable debate, a recent study has shown that the pharmacological modulation of GABA receptors in humans can increase the predominance of exclusive perceptual dominance relative to mixed percept (Mentch et al., 2019). Our study clearly cannot contribute to further informing knowledge of the mechanisms underpinning mixed percept, with the exception of suggesting that the regulation of these is not markedly affected by the normal aging process, at least for the age groups tested herein.

On average, our deprivation effects on ocular dominance are smaller than reported previously in younger adults (Lunghi, Daniele, et al., 2019, Binda & Lunghi 2017, Steinwurzel et al., 2020). In our main results, we chose to present ocular dominance in terms of the total time spent in the deprived (or dominant) and non-deprived (or non-dominant) eye percept (see Equation 1 from Lunghi et al., 2019) to make use of all data collected across the binocular rivalry runs, instead of taking a single estimate of central tendency (i.e. mean or median percept duration). Subtracting the pre-deprivation ocular dominance index from the

post-deprivation ocular dominance index (Figure 5A), we found approximately half the effect of deprivation as reported previously in normal-weighted adults (Lunghi et al., 2019). To directly compare the magnitude of the effect of patching with other previous work, we have also calculated a 'deprivation index' (Equation 2) based on mean percept duration, using the same method as in Binda and Lunghi (2017):

$$\frac{deprived\ eye_{pre}}{deprived\ eye_{post}} \times \frac{nondeprived\ eye_{post}}{nondeprived\ eye_{pre}} \quad \text{(Equation 2)}$$

An index of 1 indicates no change in ocular dominance after deprivation, an index of < 1 indicates increased dominance of the deprived eye, and an index of > 1 indicates increased dominance of the non-deprived eye. The mean deprivation effect in our study was smaller (mean ± standard deviation: younger 0.9 ± 0.1, older 0.9 ± 0.5) than that reported by Binda and Lunghi (2017) of 0.7 (± 0.3). There are numerous differences in experimental design that might contribute to the difference in strength of deprivation. These include methodological differences in the binocular rivalry paradigm such as the use of shutter goggles in the study of Binda and Lunghi (2017), continuous button pressing (here we asked participants to press a button only when a switch in percept was observed) and duration of test run; and the choice of dominant eye being through sighting dominance (as was the case here) or assessed from the baseline binocular rivalry data. It is also worth noting that the study of Binda and Lunghi (2017) only assessed 10 individuals and that some significant variance in the effect of deprivation was noted within that group.

Temporary occlusion is a potent method for demonstrating short-term visual system neuroplasticity, but in addition to being an experimental method, may have some direct utility in improving visual performance. There has been intense interest in this effect in the

context of treatments for sight improvement in amblyopia (Lunghi, Sframeli, et al., 2019; Sauvan et al., 2019). Amblyopia is a developmental disorder resulting in reduced visual acuity in one eye, and typically occurs due to strabismus, anisometropia or deprivation (for example due to congenital cataract), early in life. Approximately 1-5% of people have amblyopia (Webber & Wood, 2005), which carries significant risk of further visual impairment in older age, if the residual eye with better vision is damaged due to common age-related eye disease. Traditionally, therapies for amblyopia are considered effective in childhood, but more recently have been shown to maintain effectiveness into adulthood (Astle, Webb, & McGraw, 2011; Li et al., 2013; Simonsz-Toth, Joosse, & Besch, 2019). Such treatments typically involve varying the regulation of input from the two eyes to the binocular percept. Recent studies have begun to explore whether short-term occlusion of the amblyopic eye (which is counter to traditional therapies that occlude the "good" eye in order to make the amblyopic eye work) can be used to upregulate the visual system to respond to input from the amblyopic eye after patch removal (Lunghi, Sframeli, et al., 2019; Sauvan et al., 2019). Our findings suggest that these effects should be maintained in older age. Future studies are required to determine whether occlusion driven neuroplastic responses can be exploited to improve perceptual training in older adults, not only for amblyopia, but to perhaps improve perceptual retraining post visual loss due to age-related eye disease.

5. Conclusions

The older brain is able to rapidly adjust to changes in perceptual experience induced by temporary eye occlusion similarly to that observed previously in younger adults. We find no

evidence for a reduction in this ability. Previous studies have shown that visual perceptual learning methods are often equally as effective in older as in younger adults (DeLoss, Watanabe, & Andersen, 2015; McKendrick & Battista, 2013). Our data provides additional evidence for the ability of the older brain to dynamically respond to local visual experience and demonstrates that visual plasticity is maintained throughout the lifespan.

6. Appendices

Supplementary Material A contains all individual data for a) age, b) percentage time spent in dominant percept, non-dominant percept and mixed percept; c) switches per minute; d) time to first switch; e) median percept duration for dominant eye, non-dominant eye and mixed percept.

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References

Abuleil, D., McCulloch, D. L., & Thompson, B. (2019). Older Adults Exhibit Greater Visual Cortex Inhibition and Reduced Visual Cortex Plasticity Compared to Younger Adults. *Front Neurosci, 13*, 607. doi: 10.3389/fnins.2019.00607

Astle, A. T., Webb, B. S., & McGraw, P. V. (2011). Can perceptual learning be used to treat amblyopia beyond the critical period of visual development? *Ophthalmic Physiol Opt, 31*(6), 564-573. doi: 10.1111/j.1475-1313.2011.00873.x

578 Bai, J., Dong, X., He, S., & Bao, M. (2017). Monocular deprivation of Fourier phase
579 information boosts the deprived eye's dominance during interocular competition but
580 not interocular phase combination. *Neuroscience, 352*, 122-130. doi:
581 10.1016/j.neuroscience.2017.03.053
582 Baldwin, A. S., & Hess, R. F. (2018). The mechanism of short-term monocular deprivation is
583 not simple: separate effects on parallel and cross-oriented dichoptic masking. *Sci*
584 *Rep, 8*(1), 6191. doi: 10.1038/s41598-018-24584-9
585 Binda, P., Kurzawski, J. W., Lunghi, C., Biagi, L., Tosetti, M., & Morrone, M. C. (2018).
586 Response to short-term deprivation of the human adult visual cortex measured with
587 7T BOLD. *Elife, 7*. doi: 10.7554/eLife.40014
588 Blake, R. (1989). A neural theory of binocular rivalry. *Psychol Rev, 96*(1), 145-167. doi:
589 10.1037/0033-295x.96.1.145
590 Blake, R., & Logothetis, N. (2002). Visual competition. *Nat Rev Neurosci, 3*(1), 13-21. doi:
591 10.1038/nrn701
592 Carter, A. J., O'Connor, W. T., Carter, M. J., & Ungerstedt, U. (1995). Caffeine enhances
593 acetylcholine release in the hippocampus in vivo by a selective interaction with
594 adenosine A1 receptors. *J Pharmacol Exp Ther, 273*(2), 637-642.
595 Chylack, L. T., Jr., Wolfe, J. K., Singer, D. M., Leske, M. C., Bullimore, M. A., Bailey, I. L., . . .
596 Wu, S. Y. (1993). The Lens Opacities Classification System III. The Longitudinal Study
597 of Cataract Study Group. *Arch Ophthalmol, 111*(6), 831-836. doi:
598 10.1001/archopht.1993.01090060119035
599 Corradetti, R., Pedata, F., Pepeu, G., & Vannucchi, M. G. (1986). Chronic caffeine treatment
600 reduces caffeine but not adenosine effects on cortical acetylcholine release. *Br J*
601 *Pharmacol, 88*(3), 671-676. doi: 10.1111/j.1476-5381.1986.tb10249.x

602 DeLoss, D. J., Watanabe, T., & Andersen, G. J. (2015). Improving vision among older adults:
603 behavioral training to improve sight. *Psychol Sci, 26*(4), 456-466. doi:
604 10.1177/0956797614567510
605 Elliott, S. L., & Werner, J. S. (2010). Age-related changes in contrast gain related to the M
606 and P pathways. *J Vis, 10*(4), 4 1-15. doi: 10.1167/10.4.4
607 Elliott, S. L., Werner, J. S., & Webster, M. A. (2012). Individual and age-related variation in
608 chromatic contrast adaptation. *J Vis, 12*(8), 11. doi: 10.1167/12.8.11
609 Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: a flexible statistical
610 power analysis program for the social, behavioral, and biomedical sciences. *Behav*
611 *Res Methods, 39*(2), 175-191. doi: 10.3758/bf03193146
612 Hua, T., Li, G., Tang, C., Wang, Z., & Chang, S. (2009). Enhanced adaptation of visual cortical
613 cells to visual stimulation in aged cats. *Neurosci Lett, 451*(1), 25-28. doi:
614 10.1016/j.neulet.2008.12.041
615 JASP Team. (2020). JASP (Version 0.14.1)[Computer software].
616 Klink, P. C., Brascamp, J. W., Blake, R., & van Wezel, R. J. (2010). Experience-driven plasticity
617 in binocular vision. *Curr Biol, 20*(16), 1464-1469. doi: 10.1016/j.cub.2010.06.057
618 Levelt, W. J. (1967). Note on the distribution of dominance times in binocular rivalry. *Br J*
619 *Psychol, 58*(1), 143-145. doi: 10.1111/j.2044-8295.1967.tb01068.x
620 Leventhal, A. G., Wang, Y., Pu, M., Zhou, Y., & Ma, Y. (2003). GABA and its agonists improved
621 visual cortical function in senescent monkeys. *Science, 300*(5620), 812-815. doi:
622 10.1126/science.1082874
623 Li, J., Thompson, B., Deng, D., Chan, L. Y., Yu, M., & Hess, R. F. (2013). Dichoptic training
624 enables the adult amblyopic brain to learn. *Curr Biol, 23*(8), R308-309. doi:
625 10.1016/j.cub.2013.01.059

626 Lunghi, C., Burr, D. C., & Morrone, C. (2011). Brief periods of monocular deprivation disrupt
627 ocular balance in human adult visual cortex. *Curr Biol, 21*(14), R538-539. doi:
628 10.1016/j.cub.2011.06.004
629 Lunghi, C., Burr, D. C., & Morrone, M. C. (2013). Long-term effects of monocular deprivation
630 revealed with binocular rivalry gratings modulated in luminance and in color. *J Vis,*
631 *13*(6). doi: 10.1167/13.6.1
632 Lunghi, C., Daniele, G., Binda, P., Dardano, A., Ceccarini, G., Santini, F., . . . Morrone, M. C.
633 (2019). Altered Visual Plasticity in Morbidly Obese Subjects. *iScience, 22*, 206-213.
634 doi: 10.1016/j.isci.2019.11.027
635 Lunghi, C., Emir, U. E., Morrone, M. C., & Bridge, H. (2015). Short-term monocular
636 deprivation alters GABA in the adult human visual cortex. *Curr Biol, 25*(11), 1496-
637 1501. doi: 10.1016/j.cub.2015.04.021
638 Lunghi, C., & Sale, A. (2015). A cycling lane for brain rewiring. *Curr Biol, 25*(23), R1122-1123.
639 doi: 10.1016/j.cub.2015.10.026
640 Lunghi, C., Sframeli, A. T., Lepri, A., Lepri, M., Lisi, D., Sale, A., & Morrone, M. C. (2019). A
641 new counterintuitive training for adult amblyopia. *Ann Clin Transl Neurol, 6*(2), 274-
642 284. doi: 10.1002/acn3.698
643 McKendrick, A. M., & Battista, J. (2013). Perceptual learning of contour integration is not
644 compromised in the elderly. *J Vis, 13*(1), 5. doi: 10.1167/13.1.5
645 McKendrick, A. M., Chan, Y. M., & Nguyen, B. N. (2018). Spatial vision in older adults:
646 perceptual changes and neural bases. *Ophthalmic Physiol Opt, 38*(4), 363-375. doi:
647 10.1111/opo.12565

Mentch, J., Spiegel, A., Ricciardi, C., & Robertson, C. E. (2019). GABAergic Inhibition Gates Perceptual Awareness During Binocular Rivalry. *J Neurosci, 39*(42), 8398-8407. doi: 10.1523/JNEUROSCI.0836-19.2019

Nguyen, B. N., & McKendrick, A. M. (2016). Visual Contextual Effects of Orientation, Contrast, Flicker, and Luminance: All Are Affected by Normal Aging. *Front Aging Neurosci, 8*, 79. doi: 10.3389/fnagi.2016.00079

Pitchaimuthu, K., Wu, Q. Z., Carter, O., Nguyen, B. N., Ahn, S., Egan, G. F., & McKendrick, A. M. (2017). Occipital GABA levels in older adults and their relationship to visual perceptual suppression. *Sci Rep, 7*(1), 14231. doi: 10.1038/s41598-017-14577-5

Ramamurthy, M., & Blaser, E. (2018). Assessing the kaleidoscope of monocular deprivation effects. *J Vis, 18*(13), 14. doi: 10.1167/18.13.14

Said, C. P., & Heeger, D. J. (2013). A model of binocular rivalry and cross-orientation suppression. *PLoS Comput Biol, 9*(3), e1002991. doi: 10.1371/journal.pcbi.1002991

Sauvan, L., Stolowy, N., Denis, D., Matonti, F., Chavane, F., Hess, R. F., & Reynaud, A. (2019). Contribution of Short-Time Occlusion of the Amblyopic Eye to a Passive Dichoptic Video Treatment for Amblyopia beyond the Critical Period. *Neural Plast, 2019*, 6208414. doi: 10.1155/2019/6208414

Seymour, K. J., Stein, T., Clifford, C. W. G., & Sterzer, P. (2018). Cortical suppression in human primary visual cortex predicts individual differences in illusory tilt perception. *Journal of Vision, 18*(3), 1-8.

Sheynin, Y., Chamoun, M., Baldwin, A. S., Rosa-Neto, P., Hess, R. F., & Vaucher, E. (2019). Cholinergic Potentiation Alters Perceptual Eye Dominance Plasticity Induced by a Few Hours of Monocular Patching in Adults. *Front Neurosci, 13*, 22. doi: 10.3389/fnins.2019.00022

672 Sheynin, Y., Proulx, S., & Hess, R. F. (2019). Temporary monocular occlusion facilitates
673 binocular fusion during rivalry. *J Vis, 19*(5), 23. doi: 10.1167/19.5.23
674 Simonsz-Toth, B., Joosse, M. V., & Besch, D. (2019). Refractive adaptation and efficacy of
675 occlusion therapy in untreated amblyopic patients aged 12 to 40 years. *Graefes Arch*
676 *Clin Exp Ophthalmol, 257*(2), 379-389. doi: 10.1007/s00417-018-4170-y
677 Stanley, J., Forte, J. D., Cavanagh, P., & Carter, O. (2011). Onset rivalry: the initial dominance
678 phase is independent of ongoing perceptual alternations. *Front Hum Neurosci, 5*,
679 140. doi: 10.3389/fnhum.2011.00140
680 Steinwurzel, C., Animali, S., Cicchini, G. M., Morrone, M. C., & Binda, P. (2020). Using
681 psychophysical performance to predict short-term ocular dominance plasticity in
682 human adults. *J Vis, 20*(7), 6. doi: 10.1167/jov.20.7.6
683 Tong, F., Meng, M., & Blake, R. (2006). Neural bases of binocular rivalry. *Trends Cogn Sci,*
684 *10*(11), 502-511. doi: 10.1016/j.tics.2006.09.003
685 Wang, Y., Yao, Z., He, Z., Zhou, J., & Hess, R. F. (2017). The Cortical Mechanisms Underlying
686 Ocular Dominance Plasticity in Adults are Not Orientationally Selective.
687 *Neuroscience, 367*, 121-126. doi: 10.1016/j.neuroscience.2017.10.030
688 Webber, A. L., & Wood, J. (2005). Amblyopia: prevalence, natural history, functional effects
689 and treatment. *Clin Exp Optom, 88*(6), 365-375. doi: 10.1111/j.1444-
690 0938.2005.tb05102.x
691 Woods, D. L., Wyma, J. M., Yund, E. W., Herron, T. J., & Reed, B. (2015). Age-related slowing
692 of response selection and production in a visual choice reaction time task. *Front Hum*
693 *Neurosci, 9*, 193. doi: 10.3389/fnhum.2015.00193

694 Zhou, J., Baker, D. H., Simard, M., Saint-Amour, D., & Hess, R. F. (2015). Short-term
695 monocular patching boosts the patched eye's response in visual cortex. *Restor*
696 *Neurol Neurosci, 33*(3), 381-387. doi: 10.3233/RNN-140472
697 Zhou, J., Clavagnier, S., & Hess, R. F. (2013). Short-term monocular deprivation strengthens
698 the patched eye's contribution to binocular combination. *J Vis, 13*(5). doi:
699 10.1167/13.5.12

700