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Beyond Monocular Deprivation: Context-Dependent Plasticity in the Adult Visual System

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Abstract

This thesis is inspired by the questions: what mechanisms underlie short-term ocular dominance plasticity in the adult visual cortex, and what does this phenomenon reveal about residual plasticity beyond the developmental critical period? As a first approach to the field of study, I performed a meta-analysis of the nearly 80 studies published in the last 10 years on short-term monocular deprivation; this established the robustness of the effect and broadened its interpretation beyond simple sensory deprivation. I followed this up with an experimental approach where I substituted monocular deprivation with monocular delay to demonstrate that interocular mismatch during active visuomotor engagement is sufficient to induce plasticity. Finally, I showed that goal-directed action enhances the classical monocular deprivation effect. Together, these findings converge in suggesting that short-term plasticity is a context-sensitive mechanism shaped by sensorimotor predictions and behavioral relevance.

Summary

Recent studies have demonstrated that the visual cortex can undergo short-term, experience-dependent reorganization in response to brief monocular deprivation (minutes/hours). Although this is a robust and replicable effect, its mechanisms remain largely unknown and so does the relation between this short-term effect and the long-term plasticity phenomena that are characteristic of the developmental “critical periods”. The aim of this thesis is to investigate the mechanisms subtending short-term ocular dominance plasticity, using it as a model to understand the residual plasticity of the adult brain and to identify new ways to stimulate plasticity, with important consequences in multiple clinical conditions such as amblyopia and other disorders of binocular vision.

The first chapter is dedicated to a meta-analysis of all studies on short-term monocular deprivation in humans, which revealed the robustness of the plasticity effect and its reliability in a variety of experimental contexts. In addition, a smaller set of studies observed that similar shift of ocular dominance could be produced by manipulations that did not deprive the monocular visual input but distorted or otherwise interfered with it. This observation broadens the interpretation of short-term ocular dominance plasticity, suggesting that its underlying mechanisms may not depend exclusively on the reduction of sensory drive, but rather on the mismatch or alteration of binocular correspondence, such as when the visual input in one eye is temporally delayed relative to the other.

In the second chapter, we explored one such paradigm, showing that merely delaying the visual input in one eye is sufficient to produce the same ocular dominance shift that is achieved by depriving the same eye for the same amount of time (one hour). Importantly, the effect of monocular delay was contingent upon the task performed by the participants, who needed to be engaged in a visuomotor coordination task. This finding highlights the interaction between sensory and motor systems in

driving short-term cortical reorganization, suggesting that active engagement and prediction of sensory outcomes may play a key role in modulating plasticity.

In the last chapter, we asked whether the execution of visually guided voluntary actions during the deprivation period would similarly enhance the effect of short-term monocular deprivation and found evidence in support of this hypothesis. These results indicate that short-term plasticity in the adult visual cortex is a flexible and multi-modal phenomenon, influenced not only by the physical properties of the visual input but also by behavioral context and top-down modulation.

In a final general discussion, we integrate the findings from the three studies and examine their theoretical implications. These findings which challenge the prevailing interpretation that this phenomenon reflects a form of homeostatic plasticity – a compensatory adjustment of synaptic efficacy that serves to stabilize neuronal activity following transient reductions in input. Instead, we discuss how the results align with a predictive coding framework, according to which the visual cortex continuously updates internal models to minimize sensory prediction errors. On this view, plasticity is stimulated by failed expectations: an innovative perspective.

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Introduction

Neuroplasticity is the ability of the brain to modify its structural and functional connections in response to experience and environmental demands [1]. Plasticity is not uniformly expressed throughout the lifespan. It is well established that during early postnatal development, neural circuits undergo profound modifications under the influence of sensory and environmental inputs. These temporally restricted windows of heightened sensitivity – each associated with specific sensory systems of functional properties – are known as “critical periods”, during which external stimuli play a crucial role in shaping the mature organization and function of neural networks [2,3].

The visual system has long served as a model for studying the mechanisms and physiological bases of neural plasticity. Its well-characterized anatomical organization and clearly defined hierarchical processing pathways make it particularly suitable for experimental investigation. In the primary visual cortex (V1, Brodmann area 17), neurons exhibit a strong eye preference, responding predominantly to stimulation of one eye or the other. In layer IV of V1, thalamocortical inputs from the two eyes remain partially segregated and are organized in ocular dominance columns, alternating stripes of cells preferentially driven by one eye. However, this segregation is not absolute: neurons in supragranular and infragranular layers integrate input from both eyes, giving rise to binocular responses that form the neural basis of stereoscopic vision [3,4].

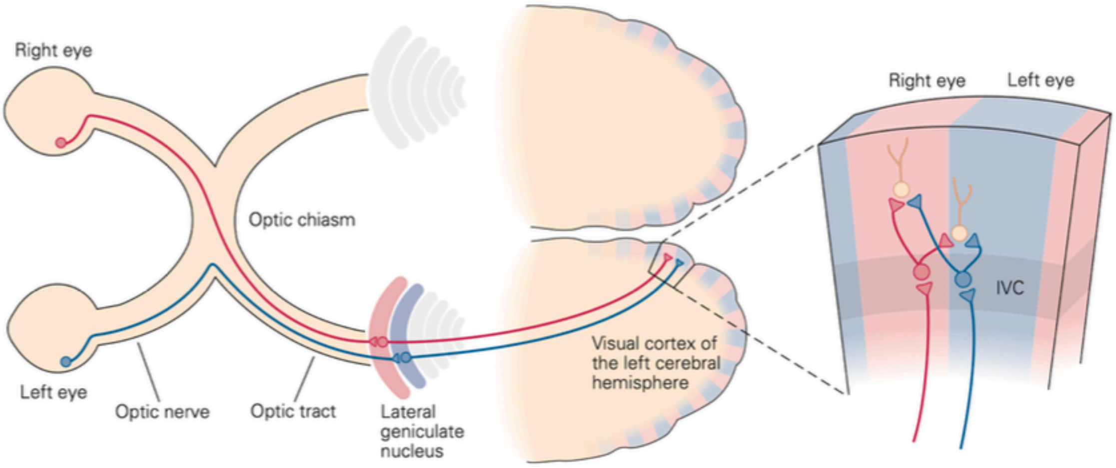

Figure 0-1 *Organization of the early visual pathway and ocular dominance columns. Visual input from the two eyes remains segregated in eye-specific layers of the lateral geniculate nucleus and in alternating ocular dominance columns in layer IVC of primary visual cortex, before converging onto binocular neurons in layers above and below layer IVC (Image from Kandel et al. 2021 Principles of neural science. McGraw-Hill).*

Seminal work by Hubel and Wiesel in the 1960s provided a fundamental demonstration of how sensory experience shapes visual cortical circuits, particularly those involved in ocular dominance [5,6]. By suturing one eye of kittens for a period of several weeks during early postnatal life, they observed a marked reduction in the number of neurons responsive to the deprived eye, accompanied by a compensatory increase in neurons driven by the open eye. This experience-dependent reorganization resulted in a persistent shift of ocular dominance, ultimately leading to amblyopia, or "lazy eye," a visual deficit that, if not treated during early development, was traditionally considered largely irreversible even after restoring normal vision [5–7]. Although more recent studies suggest that some degree of functional recovery may be possible under specific conditions, the classical view established by these pioneering experiments emphasized the existence of a temporally restricted critical period for binocular vision development. These findings exemplify the principle of Hebbian plasticity – the idea that synaptic connections are strengthened or weakened based on correlated neuronal activity, or “cells that fire together wire together” [8]. During the critical period, such Hebbian mechanisms dominate cortical development, allowing experience to fine-tune synaptic connectivity [3].

Importantly, when the same monocular deprivation procedure was applied to adult animals, no persistent changes in ocular dominance were observed, highlighting the existence of a temporally restricted critical period for binocular vision development [6]. The paradigm established by Hubel and Wiesel has since become a cornerstone in the study of experience-dependent plasticity across species, including primates [3].

Analogous processes occur in humans. Abnormal early visual experiences – such as those caused by congenital cataracts, strabismus, or uncorrected refractive errors – can similarly lead to amblyopia if not treated during childhood [7]. In humans, the critical period for binocular vision extends roughly from birth to around seven or eight years of age, after which therapeutic interventions (e.g., occlusion therapy) become progressively less effective [7]. For decades after this experimental evidence, the adult brain was regarded as largely hard-wired, with its sensory circuits fixed after the closure of developmental critical periods. However, growing evidence over the last two decades has challenged this view, showing that the adult visual cortex retains a residual capacity for plasticity. Efforts to reactivate juvenile-like plasticity in adult animal models have raised the possibility that the mechanisms underlying critical period closure may be at least partially reversible, providing new perspectives for amblyopia treatment and visual rehabilitation [9].

Recent studies in adult humans have demonstrated that the visual cortex can undergo short-term, experience-dependent reorganization in response to brief monocular deprivation (minutes/hours). Temporary occlusion of one eye for approximately two hours leads to a paradoxical shift of ocular dominance in favor of the deprived eye [10,11] – opposite in direction to the developmental consequences of long-term deprivation. The prevailing interpretation is that this phenomenon reflects a form of homeostatic plasticity: a compensatory adjustment of synaptic efficacy that serves to stabilize neuronal activity following transient reductions in input [12,3].

However, accumulating evidence indicates that the same short-term ocular dominance plasticity can also be elicited by manipulations that does not deprive the visual input, but instead alter its temporal structure, coherence or behavioral relevance. These findings raise a fundamental question: is short-term ocular dominance plasticity in the adult brain driven purely by homeostatic compensation for reduced input, or does it reflect a more general mechanism sensitive to interocular mismatch and prediction errors?

The central aim of this thesis is to address this question. By combining a quantitative synthesis of the literature with experimental manipulations that dissociate sensory deprivation from interocular conflict or combine it with behavioral engagement, this work seeks to clarify the mechanisms underlying short-term plasticity and to evaluate whether its dynamics are better explained within a strictly homeostatic framework or in light of predictive models of cortical function.

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CHAPTER 1:

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Short-term monocular deprivation in healthy humans: a meta-analysis and new perspectives

Introduction

Wearing an eye-patch over one eye for a brief period of time (minutes or hours) transiently shifts ocular dominance in favor of the patched eye. This surprising phenomenon was first highlighted by Lunghi et al. in 2011 [1], followed by Zhou et al. in 2013 [2], and then by a large set of studies, a subset of which [1-73] we meta-analyzed.

The effect of short-term monocular deprivation is very different from that of long-term monocular deprivation (days or months), classically studied during developmental “critical periods” [74-76]. While the short-term effect consists of a transient boost of the deprived eye, the long-term effect is a persistent suppression of the deprived eye, also known as amblyopia. This long-term plasticity is generally limited to early development [77], and involves both Hebbian and homeostatic mechanisms [78-80, 77]; in contrast, the short-term effect is observed throughout our lifespan [41, 62] and it is often interpreted as a form of homeostatic plasticity.

To our knowledge, the earliest investigations of short-term monocular deprivation were carried out by Zubek & Bross in the 1970s [81-83], who studied adult human volunteers and showed a biphasic modulation of temporal resolution in the non-deprived eye, briefly impaired in the first few hours and then enhanced for several days. A biphasic effect was also observed by Xu et al. [84, 85], who tested the effect of repeatedly removing stimulation from one eye or shifting attention away from it. Immediately after each 1h session there was a transient shift of ocular dominance in favor of the deprived or unattended eye, but after repeating the protocol on 10 consecutive days there was a persistent shift in the opposite direction.

The publication by Lunghi et al. [1] brought the focus on the transient shift of ocular dominance in favor of the deprived eye, which was then repeatedly observed with a variety of measuring techniques and multiple variants of the experimental design. This large body of work has never been systematically and comprehensively described; our first aim was to conduct a census of the approaches used to study this phenomenon. Following the PICO framework (Population, Intervention, Comparator, Outcome), commonly used to structure systematic reviews [86], we selected studies in healthy human participants (Population), which represent the largest majority (readers interested in a clinical perspective on this literature are referred to three recent reviews [87-89]). We focused on studies that applied short-term monocular manipulations (Intervention), using different experimental designs and diverse measurement techniques (Comparator) to measure an ocular dominance shift (Outcome). By combining results across studies, we compared the ability of different measurement techniques to reveal the short-term monocular deprivation effect and identified the main factors modulating its size and dynamics. We also assessed the effect of other short-term monocular manipulations, such as monocular image distortions and attentional manipulations. Based on these analyses, we discuss competing hypotheses on the mechanisms that may underly this short-term plasticity.

Methods

Search protocol and exclusion criteria

We followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement [90] and checklist guidelines. A systematic search was conducted across two databases (Web of Science and PubMed) on April 11th, 2025, using Boolean search terms: ‘Monocular Deprivation’ or ‘Monocular Patching’ or ‘Ocular dominance plasticity’, excluding publications before

2011, all reviews/editorials and all publications in languages other than English. This resulted in 1222 publications in Web of Science and 685 publications in PubMed; to these we added one entry [10] that was cited in relevant reviews. This resulted in a total of 1284 non-duplicated items. We screened their titles and abstracts to exclude: (i) studies in animal models, (ii) studies in human patients (any clinical condition), (iii) abstract-only publications. Figure 1-4 in the Supplementary Material shows the flow chart adopted to select the final set of 73 publications, which we included in our review.

For our quantitative meta-analysis, we extracted individual datasets from all the experiments reported in each publication, which totaled 292. The age-range of tested participants was 10-81 years.

We analyzed a subset of these (N=153), after excluding: (i) datasets from which we could not extract a measure of ocular dominance shift (e.g. resting-state brain activity) or convert it into an effect-size estimate (e.g. no individual participants' data were available, see also Supplementary Table S1); (ii) experiments that manipulated vision in both eyes (e.g. by alternating deprivation across eyes [50] or by exposing the non-deprived eye to impoverished visual information [38]) or in neither eye (e.g., control experiments with no manipulation); (iii) experiments where the monocular manipulation was combined with other manipulations (e.g. pharmacological manipulations, brain stimulation, physical activity); (iv) datasets that included less than 4 participants or (v) were re-plotted from a previous publication; (vi) datasets collected in patients (e.g. with amblyopia). We provide a Data File (https://doi.org/10.5281/zenodo.17414109) listing all datasets with their main characteristics, and motivating exclusions according to the above six categories.

Effect-size computation

We quantified the impact of each manipulation by taking the shift of ocular dominance after the monocular manipulation. Supplementary Table S1 summarizes the transformations used to obtain this index from the data available in the source publications. These transformations ensured that, across all datasets, positive values indicate a shift of ocular dominance in favor of the deprived (or manipulated) eye and 0 represents no effect. Even after these transformations, effects were expressed in disparate units of measurement (e.g. percentages, degrees of visual angle); we therefore expressed them all in units of standard deviation (like in Cohen's d [91]) and obtained an effect-size index that could be compared across all publications.

In several publications, the effect of monocular manipulations was evaluated at multiple time-points. For the main analysis, we used the first measurement, which often was the peak effect; note that studies differ markedly in the duration of the time-window over which this first measurement was averaged, from less than 3 minutes [2] to more than 12 minutes [55]. In an additional analysis, we examined the decay rate of the effect, pooling across experiments that used black-and-white stimuli (given the reportedly different dynamics of the effect measured with colored stimuli [5]). This analysis was designed to be orthogonal with respect to the main one, abstracting from differences in the peak effect size and comparing how long it took for the effect to decay. This required applying a different transformation to the source data (detailed in Supplementary Table S2), to ensure that the effect was represented on a linear scale. We reported these data in a series of plots (examples in Supplementary Figure 1-6), with the effect decaying exponentially as a function of the delay from the end of the manipulation. We fit each curve with an exponential function in the form $y = a^x + b$, and used it to estimate the proportion of residual effect 30 min after the end of the manipulation.

Software and statistical approach

All graphical representations and statistics were performed in Matlab [92], and R [93]. In R, we used the ***metafor*** package [94] specifically designed for meta-analysis. A **random-effects model** was fitted using restricted maximum likelihood to obtain a pooled estimate of the effect size across the k included datasets. Significance was assessed with a z-test. Heterogeneity across datasets was quantified with **Cochran's Q test** and the **I^2 statistic**. To investigate the factors potentially contributing to this heterogeneity, we ran a mixed-effects **model** with six regressors: (i) the technique used to measure ocular dominance (monocular, binocular competition, binocular cooperation), (ii) the type of deprivation (opaque vs. translucent patching), (iii) whether the dominant or non-dominant eye was deprived, (iv) the duration of deprivation, (v) the sample size, and (vi) the publication year. The statistical contribution of each factor was evaluated with omnibus tests of moderators (**QM**). To evaluate differences between techniques, we used a permutation test after fitting the mixed-effect model **with the Knapp-Hartung adjustment (“**knha”**)**. For the generation of forest and funnel plots, effect sizes were paired with standard errors computed as $\sqrt{\frac{1}{sample\ size}+\frac{d^2}{2 \times sample\ size}}$ where *d* is the effect size. The impact of **publication bias** was evaluated with the Egger’s regression test for asymmetry. This was complemented with a “**trim and fill” procedure**, which estimates the number of hypothetically missing studies due to selective reporting of positive findings, recalculating the pooled effect size and its significance after inclusion of the hypothetically missing null findings. Additional sensitivity analyses (leave-one-out and influence diagnostic) and quality assessments are described in the Supplementary Material.

Results for monocular deprivation studies

Out of the 153 datasets we analyzed, 114 measured the effects of short-term monocular deprivation, achieved by applying a monocular patch, either translucent or opaque, or by nulling the contrast in one eye under dichoptic viewing conditions [12, 21, 34]. Pooling across these datasets, the grand average of the ocular dominance shift was large: 1.4 units of standard deviation. A chronologically ordered representation of these datasets is presented in a forest plot in Supplementary Figure 1-5. Only 16 datasets showed a non-significant ocular dominance shift [21, 24, 25, 28] [38, 40, 43, 56, 62]. Importantly, none of the datasets reported a statistically significant shift favoring the non-deprived eye. These null findings were obtained with similar techniques and deprivation approaches as used in studies with positive results, suggesting that they may be related to experimental noise. To assess overall significance, we entered the data in a random-effects model, which returned a highly significant effect (k = 114; z = 20.3, p <0.0001) with a high level of heterogeneity (I^2 = 67.24%, Q(113) = 321, p <0.0001). We investigated the sources of such heterogeneity by testing the impact of several key modulators with a mixed-effects model, which we describe next.

We first considered the impact of the technique used to measure ocular dominance (y-axis of Figure 1-1). We grouped techniques into three categories (analytically presented in the Supplementary Results): stimulating each eye separately (monocular), stimulating the two eyes with incongruent images that do not fuse (binocular competition) or fuse into a unitary percept (binocular cooperation). Thus described, this factor significantly influenced effect-size estimates (accounting for 5.4% of heterogeneity, statistically significant: QM(2) = 6.2 p = 0.0435). Direct comparison across the three categories indicated a tendency for larger effects with binocular cooperation techniques versus both binocular competition (permutation test following the mixed-effects model: F(2, 111) = 176.8, p = 0.035) and monocular techniques (F(2, 111) = 97.7, p = 0.0521), with no difference between the latter two (F(2, 111) = 104.2 p = 0.9647). These results indicate that the effect of short-term monocular deprivation was robust and easily measured with both binocular and monocular techniques, with a mild preference for binocular cooperation.

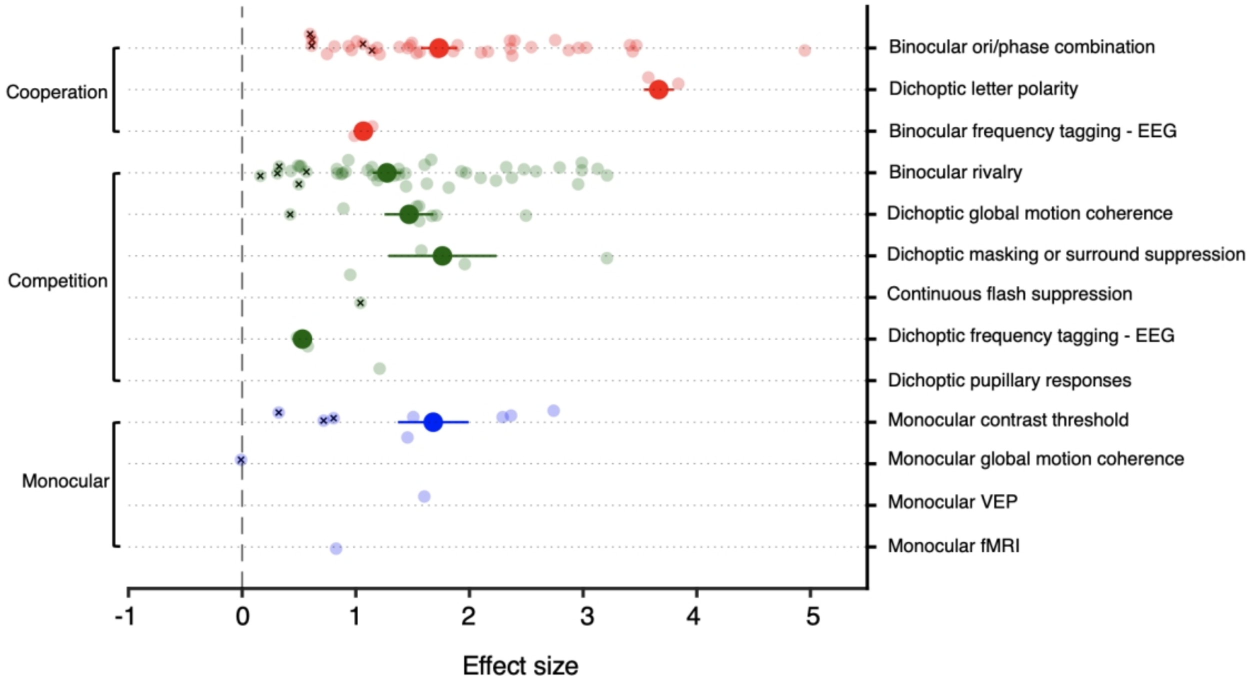

Figure 1-1 *Effects of short-term monocular deprivation on ocular dominance (x-axis) measured with different techniques (y-axis). Each point represents one dataset, except larger filled symbols reporting the average effect for each technique. We grouped techniques into three categories (red: cooperation techniques, green: competition techniques, blue: monocular techniques). Crossed-out symbols*

indicate non-significant effects; see also a forest plot representation of the same datasets in Supplementary Figure 1-5

The second factor we considered was the duration of short-term monocular deprivation, which varied widely (from 15 to 600 minutes); as expected, this had a significant influence over effect-size estimates (accounting for 10.2% of heterogeneity, statistically significant: QM(1) = 4.9, p = 0.0269). This is shown in Figure 1-2A, where the same results presented in Figure 1-1 are aggregated according to deprivation duration, showing a positive relationship between deprivation duration and effect-size. This observation, obtained by pooling across studies, is in line with the conclusions of the few studies (n=8) that tested more than one deprivation duration [5, 24, 29, 43, 45, 52, 56, 63]; five of these provided evidence for a larger effect at longer durations [5] [29, 52, 63], according to a saturation function ceiling around 5h [43]. The other four studies gave more uncertain results: in two cases, effect sizes were similar across tested durations [24, 45]; in another, there was a positive correlation between duration and effect size but only when ocular dominance was measured with binocular rivalry, not with a letter polarity test [56]. Thus, evidence from both within- and across-study analyses consistently indicated that longer monocular deprivations induce stronger ocular dominance changes.

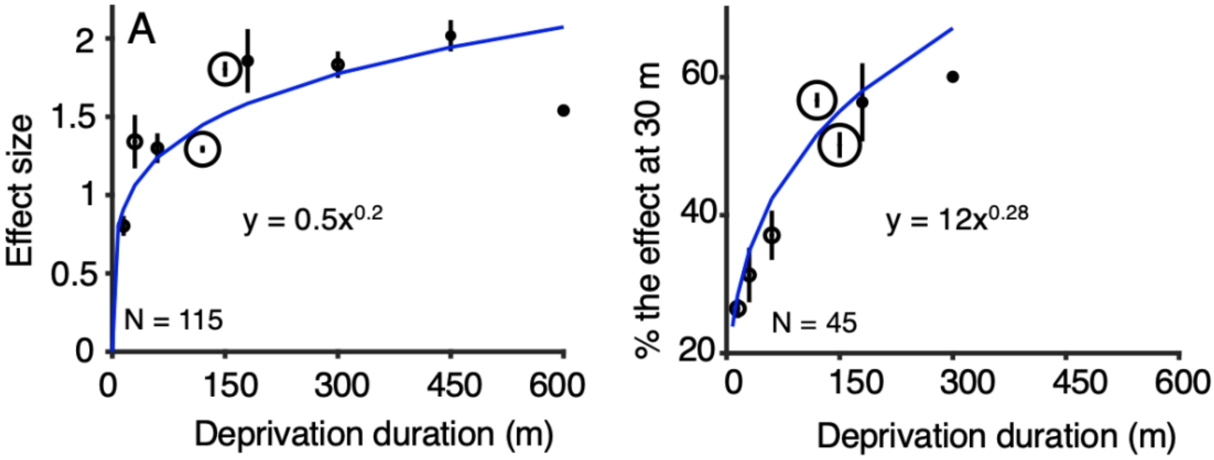

Figure 1-2 *The dose-response curve of the short-term monocular deprivation effect and its persistence. A) Relationship between deprivation duration and effect size. B) Residual effect 30 minutes after deprivation, reported against deprivation duration. For both panels, marker size reflects the number of studies contributing to each time point. The blue line shows the best fit exponential function whose equation is reported in figure.*

A related question is whether longer deprivations promote longer-lasting effects. To our knowledge, no study addressed this question, which we tackled by considering the subset of datasets for which the decay rate of the deprivation effect could be estimated (n=47). These studies reported the ocular dominance shift at multiple time-points after the end of the deprivation; these were transformed to express each datapoint as a percentage of the effect registered at the first time-point (immediately at the end of the deprivation) and the distribution was fit with an exponential function to estimate the residual effect at 30 minute delay (see Supplementary Table S2 and related text for more details on the transformations and the fit functions). As shown in Figure 1-2B and Supplementary Figure 1-6, longer deprivation durations were systematically associated with longer-lasting effects, indicating that deprivation duration influenced both the magnitude of the effect and its persistence. Two studies asked whether the short-term monocular deprivation effect could be “kept in storage” by interrupting all visual stimulation at the end of deprivation; they found that dark exposure can prolong the effect for about one hour [61] (not two hours [51]). However, a much longer retention interval was possible if participants went to sleep at the end of the deprivation [51]. These results suggest that the decay of the deprivation effect is governed by multiple factors. Since the decay is not constant (it is delayed with longer deprivations and by going to sleep [51]), restoration of the normal visual input at the end of deprivation cannot be the only governing factor; of course, this remains an important factor, given that total darkness slows down the recovery of normal ocular dominance [61].

Another related point is whether the effects can be integrated across separate short-term monocular deprivation sessions. Considering the typical decay rate for a 2h long deprivation, one would estimate that only a small percentage of the effect would be left after 2h or more. Assuming linear behavior, this predicts that monocular deprivations separated by few minutes should integrate their effects, as shown in the three studies that briefly interrupted deprivations to track their effect over time and reported a gradual increase of the effect-size [34, 43, 45]. It also correctly predicts that no residual effect would be measurable 24 hours after the end of a short-term monocular deprivation [12] and that the effects of short-term monocular deprivations performed 24 hours apart should be indistinguishable [28, 73]. Note, however, that studies in amblyopic patients showed that multiple daily sessions of amblyopic-eye deprivation promoted a gradual recovery of its vision [95-97]. This suggests that monocular deprivation may have physiological consequences that go beyond the transient shifts of ocular dominance and could outlast them (as previously suggested [4]), with important clinical implications.

Finally, we considered two factors previously assumed to modulate effect size: patch type and dominance of the deprived eye (Supplementary Figure 1-7). Most of the studies used a translucent patch (or equivalent dichoptic viewing procedure) to attenuate monocular contrast (n=88), while some used a light-tight patch (n=25) blocking all visual information. This factor did not significantly impact effect size (accounting for 0% of heterogeneity, non-significant: QM(1) = 0.1, p = 0.7531), in line with qualitative comparisons [2, 45]. This implies that preventing pattern vision in one eye is sufficient to shift ocular dominance, while eliminating all visual input (luminance) is not relevant. A long-standing assumption is that depriving the dominant eye is more effective than depriving the non-dominant one, as originally reported by Lunghi et al. [1] for their 8 participants. Probably as consequence, we only found n=17 experiments depriving the non-dominant eye, while n=85 deprived the dominant eye (the remaining n=12 did not impose or report a systematic association between the deprived and the dominant eye). However, this factor did not significantly affect the size of the short-term deprivation effect (accounting for 2.2% of heterogeneity, non-significant: QM(1) = 1.3, p = 0.2558). We acknowledge that this across-study approach has multiple limitations, including the heterogeneity of criteria used to identify the dominant eye (for example, some used pre-deprivation binocular rivalry or phase-combination results, others used separate tests like the Porta test). Further within-subject studies are therefore warranted.

In a mixed-effects model considering all four factors above (technique, deprivation duration, patch type and dominance of the deprived eye), they collectively accounted for about 20% of the heterogeneity in the sample, with significant residual heterogeneity (Q(97) = 244.9, p < 0.0001). This indicates that the effect of short-term monocular deprivation, although consistently observed in a vast range of experiments, varied significantly across datasets depending on multiple factors, some of which remain to be enucleated.

Supplementary Figure 1-8 and related text in the Supplementary Results present additional considerations on the impact of publication bias, a sensitivity analysis, and an overall quality assessment. Briefly, we found that the effect-size did not systematically change with publication year (which accounted for 0% of heterogeneity, non-significant: QM(1) = 1.7, p = 0.1953). However, it did co-vary with sample size (accounting for 7.1% of heterogeneity, significant: QM(1) = 9.0, p = 0.0027) leading to an asymmetrical funnel plot (z = 11.9, p <0.0001). We used the “trim and fill” method to estimate that 36 datasets with small or negative effects would be required to reach symmetry (z = 0.6, p = 0.5506). Crucially, the inclusion of these hypothetically missing datasets did not impact the significance of the effect (random-effects model with k = 150, estimate = 1.1, z = 13.2,

$p < 0.0001$). This indicates that the effect remains robust even after accounting for the impact of publication bias.

Factors interacting with short-term monocular deprivation

Figures 1-1 and 1-2 selectively considered experiments performed under very homogeneous conditions, which we clarify here by opposition with other studies that purposedly altered such conditions to test the impact of within-subject factors. While most studies ensured that visual input to the non-deprived eye had similar statistics as in normal viewing, one study dramatically reduced visual information in the non-deprived eye by letting participants watch a blank curtain for the entire deprivation duration [45]. In these conditions, the non-deprived eye received little more information than the deprived eye and the deprivation produced no reliable ocular dominance shift. Coherently, the deprivation effect was reduced when ocular dominance was measured with stimuli that were unattended during the deprivation [71].

While most studies achieved monocular deprivation by covering one eye with a patch behind which the eye remained open, one study assessed the impact of keeping the deprived eye shut [57] and reported a reduction of the deprivation effect. Shutting the deprived eye achieves a stronger deprivation, yet it produces a smaller effect.

Several studies manipulated the activity performed during deprivation, with mixed results. Engaging in moderate physical activity during the deprivation enhanced the effect in one study [10] but not in others [20, 26, 44, 46, 47]. Engaging in an orthogonal task (motor-sequence learning or working memory) reduced the deprivation effect in one study [64]; however, no modulation of the effect was observed when manipulating participants' engagement in a visuomotor task (playing action videogames, versus passively watching the game [31]). This heterogeneity suggests that a latent variable related to the experimental manipulations may have been incompletely controlled – for example, the visual consequences of these activities (e.g. amount of gaze movement during the activities) may require more detailed characterization.

Another set of studies manipulated neural excitability during deprivation. There was no effect of applying non-invasive stimulation of the occipital cortex during deprivation [47, 56]. However, the deprivation effect was enhanced when (i) participants stayed in total darkness for one hour before the deprivation [61], (ii) the deprivation was performed in the morning vs. the late evening [51] and (iii) participants had a standardized breakfast before the deprivation vs. maintained the overnight fasting [55], all conditions associated with a modulation of cortical excitability (enhanced by dark exposure [98 , 99, 100], increased in the morning vs. evening [101], and after a meal vs. fasting [102]). This suggests that enhanced cortical excitability facilitates the ocular dominance shift induced by deprivation. In contrast, the deprivation effect was reduced by administration of donepezil, a cholinesterase inhibitor [29], suggesting that increasing acetylcholine levels prevents ocular dominance from shifting in response to deprivation.

A few studies considered between-subject covariates and generally failed to detect systematic inter-individual differences in short-term monocular deprivation effects, with one exception: body mass index, which is negatively correlated with effect size [27, 39]. Deprivation effects did not vary systematically with age [41, 62], as the ocular dominance shift following short-term monocular deprivation was comparable in adolescents, young adults and elderly participants – but note that a stronger effect in the elderly participants could be revealed by onset rivalry [41]. No study reported associations between sex or gender and short-term monocular deprivation effects. One study found that the deprivation effect correlated with baseline binocular vision [37] but this correlation was not significant in other studies [45, 62]. These null findings do not exclude the existence of associations between short-term monocular deprivation effects and important dimensions of inter-individual variability; however, they indicate that, if they exist, these associations are not strong enough to be revealed with the relatively small sample sizes that are typical of this line of research.

Results for other short-term monocular manipulations

While most studies tested the effects of blocking vision in one eye, a growing number of experiments are exploring more subtle manipulations and surprisingly report essentially the same effect: a shift of ocular dominance in favor of the manipulated eye. We identified 39 datasets allowing us to compute an effect-size. These are reported in Figure 1-3 and in the forest plot of Supplementary Figure 1-9. We entered them in a similar random-effects model as used for the short-term monocular deprivation studies, which revealed a reliable effect ($k = 39$; estimate = 0.98; $z = 9.3$; $p < 0.0001$), with significant heterogeneity ($I^2 = 60\%$, $Q(38) = 84.3$, $p < 0.0001$). Given the diversity of approaches, we limit our analysis to a qualitative examination, as follows.

One manipulation that is conceptually close to monocular patching consists of partially attenuating contrast in one eye (in a dichoptic stimulation set-up). The attenuation needed to be strong (80%, not 40%) to elicit a reliable ocular dominance shift [7]. Instead, swapping the contrast attenuation between eyes (at 7Hz, [50]) did not affect ocular dominance, indicating that interfering with binocular fusion is not sufficient to elicit the shift. Selective attenuation of luminance contrast (leaving chromatic contrast unaffected) was sufficient to elicit a strong ocular dominance shift, while the opposite manipulation (attenuating chromatic contrast, leaving luminance contrast unaffected) was ineffective [21]. Attenuating contrast at one range of orientations (e.g., vertical or horizontal) elicited a strong ocular dominance shift, unselective for the orientations used for testing [18]. A strong effect was also achieved by attenuating contrast of the higher spatial frequency components, again unselective for the frequencies used for testing; however, no such effect was elicited by attenuating the lower spatial frequency components [7]. Application of a monocular neutral density filter elicited a strong ocular dominance shift only when participants viewed artificial (low luminance) stimuli, not in natural viewing conditions [19]. These results collectively indicate that short-term monocular deprivation primarily acts through reduced visibility of the high-frequency components of the image. Higher spatial frequencies are associated with lower contrast sensitivity, implying that they are most impacted by contrast attenuation. Moreover, acuity is lower for iso-luminant stimuli defined by chromatic contrast, explaining why a strong ocular dominance shift is achieved by depriving luminance contrast (leaving only iso-luminant chromatic modulations that do not efficiently carry the higher spatial frequencies). When average luminance decreases through a neutral density filter, the contrast sensitivity function shifts to the left, selectively attenuating sensitivity for the higher spatial frequencies; however, this effect is negligible in natural light, where luminance is so strong that the filter has no appreciable impact on acuity.

Crucially, an ocular dominance shift could also be induced by manipulations that did not attenuate contrast but merely distorted the image in one eye: by phase-scrambling the image presented to one eye [7], by substituting it with pink noise [12, 34, 67], or by applying a monocular kaleidoscope [25]. And even without altering the monocular image in any way, an ocular dominance shift could be induced by making the image in our eye invisible [15, 33] through continuous flash suppression (note that this effect was already present in the 2010 report by Ooi et al. [84]).

A final set of studies selectively mismatched the monocular image with its multimodal context. This was achieved in one of three ways: (i) with a monocular inverting prism [45]; (ii) by reversing the temporal order of movie-frames in one eye [65, 69, 70]; (iii) by delaying one eye by 1/3 of a second to make it useless for visuomotor coordination [66]. In all three cases, ocular dominance shifted in favor of the manipulated eye (note that these manipulations only lasted 1h, about half the typical duration of short-term monocular deprivation, complicating the comparison of effect size across manipulations). Control experiments assigned a key role to behavioral relevance for the generation of the ocular dominance shifts; for example, monocular delay was ineffective when participants passively viewed the scene rather than engaging in a visuomotor task [66]. Moreover, the effect of temporal inversion was depleted by non-invasive inhibition of the Frontal Eye Fields [70].

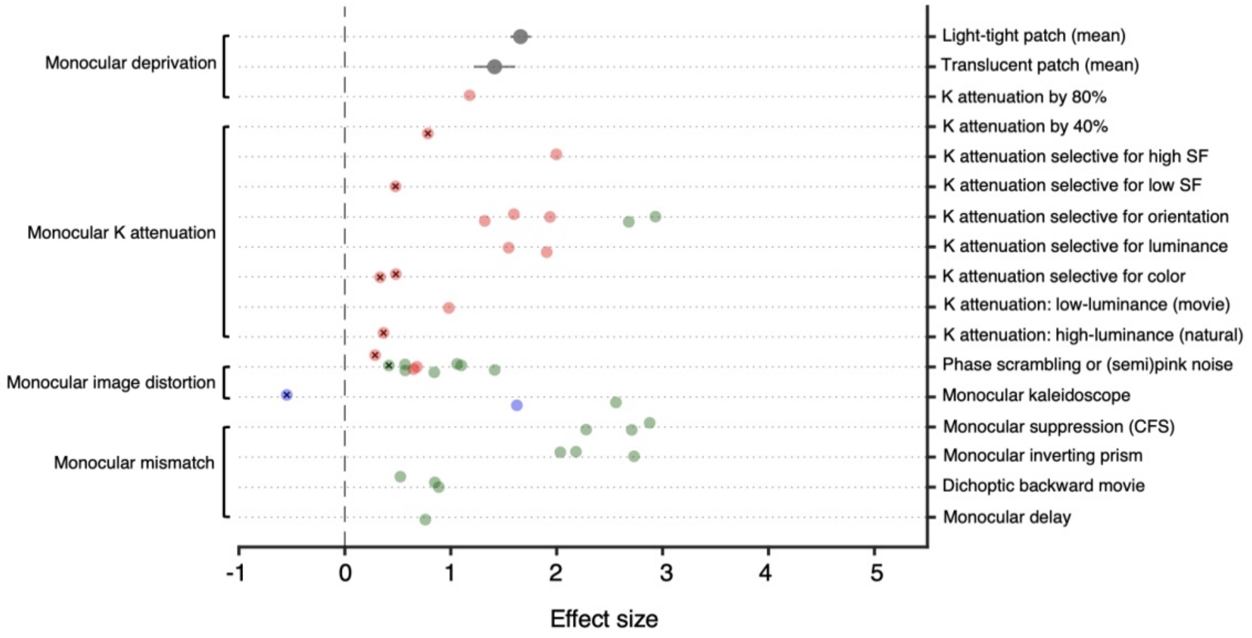

Figure 1-3 *Effects of other short-term monocular manipulations on ocular dominance (x-axis) obtained with different interventions (y-axis). Each point represents one dataset except the large gray dots at the top reporting the average effect of short-term monocular deprivation (mean and s.e.m. across datasets in Figure 1-1). Crossed-out symbols indicate non-significant effects. Colors use the same conventions as in Figure 1-1 and represent the technique used for measuring ocular dominance. K: contrast. SF: Spatial Frequencies. CFS: Continuous Flash Suppression; see also a forest plot representation of the same datasets in Supplementary Figure 1-9.*

It is interesting to consider the few examples where multiple techniques were used to test the same or similar manipulations. This was the case for monocular image distortion, where the ocular dominance shift was selectively observed with binocular competition techniques, not with binocular cooperation [7, 12]. Based on a multi-stage model of binocular processing [103], these authors suggested that monocular distortion could impact ocular dominance at a later stage than short-term monocular deprivation, sparing monocular and binocular cooperation stages. However, this model is inconsistent with data from the monocular kaleidoscope manipulation (another type of monocular distortion), which produced similar effects on both binocular competition and monocular contrast sensitivity [25].

It is also informative to compare studies testing the effects of different manipulations with the same technique. Binocular rivalry and steady-state visual evoked EEG responses elicited by incompatible stimuli in the two eyes, were tested for two manipulations: monocular deprivation (nulling contrast in one eye [67]) and monocular mismatching (dichoptic backward movie [70]), revealing similar effects. However, steady-state visual evoked EEG responses elicited by compatible binocular stimuli only revealed an effect of monocular deprivation [34] (and monocular distortion, i.e. presenting pink noise in one eye [34]), but no effect of the dichoptic backward movie manipulation [65]. Some of these studies additionally analyzed intermodulation frequency responses, which estimate the strength of inter-ocular competition. This was reduced by the dichoptic backward movie manipulation [70], but unaffected by monocular deprivation [67].

Discussion

This is the first meta-analysis comprehensively compiling more than 150 datasets from the nearly 15 years of short-term monocular manipulation studies. The key strength lays in the large number of datasets measuring the same outcome (ocular dominance), which allowed us to pool across studies to test the impact of key modulators of the effect.

Most datasets measured a significant positive effect, a transient shift of ocular dominance towards the deprived eye. We assessed the impact of publication bias; our analysis indicate that the effect of short-term monocular deprivation is robust and remains significant even after accounting for the probable unreported datasets with null or negative effects.

We found that effect size varies depending on the technique used for measuring ocular dominance. However, while binocular cooperation techniques revealed larger effects on average, a significant ocular dominance shift was observed with a wide range of approaches, both monocular and binocular, both behavioral and physiological. This further testifies to the robustness of the effect.

We also identified deprivation duration as a key modulating factor, with longer durations promoting larger and longer lasting effects. Extrapolating from the observed curves, one would predict that extremely long deprivations (days or weeks) could promote stable ocular dominance changes – crucially, in the direction opposite to the long-term monocular deprivation effects observed during development [74-76]. This paradoxical observation emphasizes the need for additional experimentation, with longer lasting monocular deprivations assessed in adults with the same techniques meta-analyzed here.

The effect of short-term monocular deprivation was comparable when vision in one eye was completely blocked with a light-tight patch or merely attenuated in contrast, indicating that the strength of visual stimulation is not the only parameter regulating the effect. In addition, a qualitatively similar ocular dominance shift could be elicited by other manipulations that do not reduce the strength of the monocular input. This raises the question whether the same mechanism(s) account for both the effect of short-term monocular deprivation and of other monocular manipulations – discussed below.

Even after accounting for the above key modulators, a large unexplained heterogeneity characterized the analyzed data, indicating that additional factors were not enucleated – an important limitation of our analysis. Other limitations include the small sample-size of some of the datasets (even after excluding datasets with less than 4 participants, the average sample-size was about 12) and the limited reporting of sex and age of the participants, which prevented us from systematically assessing the impact of these variables.

While our quantitative analyses focused on ocular dominance measurements after short-term monocular deprivation, the Supplementary Material also includes a narrative assessment of other outcome measures (e.g., resting-state brain connectivity [104] and rhythms [58]) and of the interaction between short-term monocular manipulations and other interventions (e.g. physical activity [10]). These results suggest that monocular manipulations have effects that extend beyond the transient ocular dominance shift and may outlast it [4].

The studies we meta-analyzed present different interpretations of the effects induced by short-term monocular deprivation and other monocular manipulations.

One discarded hypothesis is that adaptation to low contrast can account for short-term deprivation effects. A recent review listed many qualitative differences between contrast (de-)adaptation and monocular deprivation [105]. For example, the sharper vision experienced after adaptation to low contrast [106] or to blur [107-111] transfer across eyes and tend to be tuned for orientation [112, 113], the exact opposite of the effects of monocular manipulations [15, 18].

The most common hypothesis describes the effects of short-term monocular deprivation as a form of homeostatic plasticity. This generally assumes that short-term monocular deprivation promotes a gain-change in monocular processing within the primary visual cortex V1, the last cortical stage where information from the two eyes is represented separately. In line with MR spectroscopy findings [9], many have interpreted the effects of short-term monocular deprivation as resulting from reduced GABAergic inhibition in early visual processing [37, 41, 55, 62]. Such local-V1 perspective does not easily account for several complex/high-level factors that have been linked with the ocular dominance shifts. These include the observation that multisensory integration fails for the deprived eye [16] and that short-term monocular deprivation effects are modulated by motor and cognitive tasks [64]; these clearly suggest that signals from outside V1 participate in the effect, in line with evidence that short-term monocular deprivation affects feed-back modulatory signals [58].

Studies using other monocular manipulations that do not impact the strength of the monocular input proposed a range of hypotheses to explain the resulting ocular dominance shift. One possibility is that these more complex manipulations do not engage the same mechanisms that mediate monocular deprivation effects. For example, in a paradigm where the visual input in the two eyes remained of comparable strength while attention was selectively directed to one eye, the ocular dominance shift was suggested to result from impaired inter-ocular competition, with largely unaffected monocular responses [65, 69, 70]. However, most of the studies measuring the effects of complex monocular manipulations used binocular competition techniques, limiting the possibility to test this model. Further studies extending the range of techniques used to quantify the effects of complex monocular manipulations are warranted.

A second possibility is that the effects of complex monocular manipulations are obtained by mimicking the consequences of deprivation. For example, when one eye is unattended or unnoticed (due to continuous flash suppression [15] or application of a spatiotemporal inversion [45, 65], or a delay [66], the latter recently replicated in [114]) the intensity of its cortical responses could be reduced; at the end of the manipulation, this suppression could rebound into the observed boost of the manipulated eye (as suggested in [15], [45] and in the early work by Ooi et al. [84]). This model assumes that an internal gain-control regulation follows a very complex time-course, gradually shifting in one direction during the manipulation and suddenly swapping to the other direction at the end of the manipulation. Very few studies directly addressed this question and attempted to quantify monocular responses during the manipulation; the one study that reported such measurements provided evidence for the opposite modulation: an enhancement of the unattended eye [45]. Further studies monitoring visual processing during the manipulation would be important to clarify the underlying mechanism.

We take this opportunity to propose a third possibility, where the same mechanism subtends the effects of both monocular deprivation and more complex manipulations. This hypothesis starts from the assumption that predictive coding lays at the foundation of monocular manipulation effects. Predictive coding is a popular theory of neural function (specified in different models [115-119]) assuming that an important share of neural responses does not represent sensory inputs, but their deviations from predictions. These responses, for example in V1, are enhanced when the input is inconsistent with predictions, suppressed otherwise. Over a lifetime of binocular experience, our visual system sets up a strong prediction that the two eyes provide structured and congruent information. When one eye suddenly fails to match this prediction, it generates error signals. And if errors repeatedly occur for minutes or hours, the natural (Bayesian) consequence would be a downweighing of predictive signals [120] for the manipulated eye representation. Since unpredictable signals are associated with enhanced responses, the downweighing of predictive signals could explain the enhancement of the deprived/manipulated eye. On this view, deprived, filtered, distorted, inverted and delayed images are all unpredictable and incongruent with the rest of the sensorimotor input. This predicts that monocular mismatch and short-term monocular deprivation should produce comparable and correlated effects. Although there is some evidence for discrepancies in effect-size, the available data is not conclusive. We propose that further experiments are necessary, directly and quantitatively comparing the effects of short-term monocular deprivation and other manipulations with a range of techniques, both after and during the manipulation.

To conclude, there is a rich literature on how a simple manipulation like occluding/interfering with one eye for a brief time reliably impacts visual processing. However, the mechanism(s) subtending the effect(s) remain largely unknown. This lack of mechanistic understanding prevents us from establishing how the transient effects of the short-term monocular manipulations relate to the permanent effects of long-term deprivation – a question with clear clinical relevance. The present overview of the published data identified a number of directions for further experimentation that could contribute to filling this gap.

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Supplementary data

Flowchart of the selection process and exclusion criteria

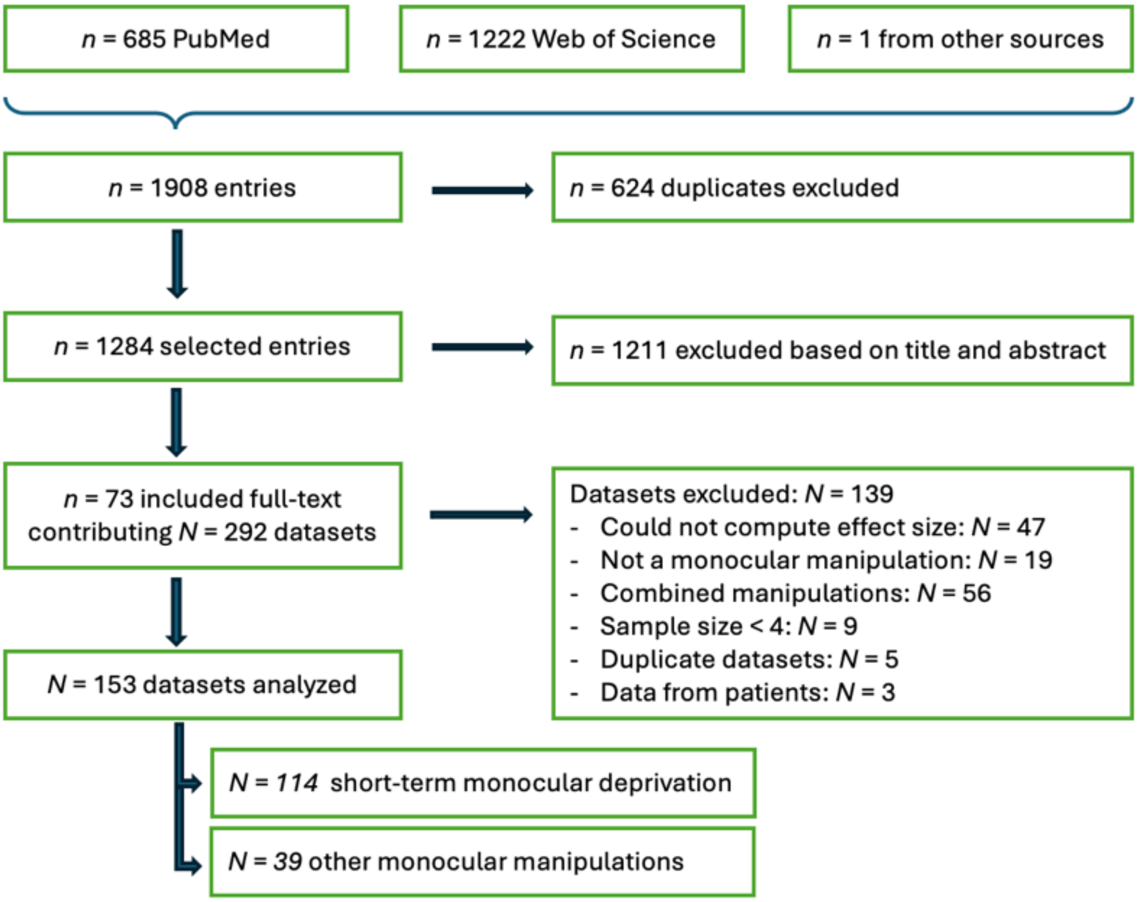

Figure 1-4 *Flowchart of the selection process. "n" stands for the number of publications, while "N" indicates the number of datasets (with multiple datasets often extracted from a single publication).*

Supplementary data file

All 292 datasets from the selected 73 publications were listed in a spreadsheet (https://doi.org/10.5281/zenodo.17414109), reporting several key features of each dataset, specifying which analysis included it and/or the reason for excluding it.

Transformations applied to raw data

Our quantitative analyses focused on the change of ocular dominance following short-term monocular deprivation or other manipulations. Studies differed in the way they defined the change of ocular dominance; in some cases, ocular dominance was not directly reported but it could be computed from values defining monocular vision (e.g. sensitivity). Supplementary Table S1 summarizes the indices extracted from the source publications and the corresponding transformations we applied to obtain an estimate of the ocular dominance change. Whenever a transformation was required, single participants' data were necessary (and datasets were excluded from the analyses if they did not report them).

In general, we extracted single participants' values (from data repositories or from the figures in the source publications, using WebPlotDigitizer (https://automeris.io/WebPlotDigitizer/), performed the transformations described in Supplementary Table S1 and then computed the mean and standard deviation of the ocular dominance change; the effect size was given by the mean divided by the standard deviation. Experiments for which single participants' data were not reported were excluded from the analysis, except when their results were already reported as ocular dominance changes, requiring no transformations (first row in Supplementary Table S1). In these cases, the effect size was computed directly from the t-tests evaluating the significance of the changes (effect-size = t-value divided by the square root of sample size minus 1) or from mean and standard error of the change (extracted from the figures or reported in-text).

Source values	**Transformation applied**	**Source data**
OD change (log-ratio, difference of post and pre or t-test comparing OD post and pre) --- OD change (inverted log-ratio)	None --------------------------------------- sign inversion	Single participants' data t-test and sample size mean, s.e. and sample size
OD change (ratio)	log10(ODchange)	Single participants' data
OD change (inverted ratio)	log10(1/ODchange)	
OD post and OD pre (ratio of the two eyes)	log10(ODpost/ODpre)	
OD post and pre (difference between eyes)	ODpost - ODpre	
change of monocular vision in each eye (post to pre log ratio or decibels) ---	Dep change – Ndep change ---------------------------------------	

change of monocular vision in each eye (post to pre ratio)	log10(Dep change / NDep change)	
monocular vision in each eye, pre and post	log10(DepPPost/ DepPre) / (NDepPost / NDepPre))	

Table S1 – Transformation applied to quantify ocular dominance change. OD stands for Ocular Dominance; Dep for deprived (or otherwise manipulated) eye, NDep for non-deprived/manipulated eye.

To analyze the decay rate of the ocular dominance shift, we pooled data from studies that reported ocular dominance changes at multiple time points following deprivation and expressed them as percentages of the effect registered at the first time-point (immediately after the end of the deprivation). This allowed us to fit the curves with an exponential function and estimate the fraction of the residual effect after a fixed delay, 30 minutes after the end of the deprivation. In order to compute percentages, we first needed to express all data-points on a linear scale, with 0 representing no effect; the required transformations are indicated in Supplementary Table S2.

Source values	**Transformation applied for the decay-rate analysis**
OD change (post - pre)	none
OD change (ratio)	ODchange-1
OD change (log-ratio)	$(10^{\mathrm{ODchange}})-1$
OD change (decibels)	$(10^{\mathrm{ODchange}/20})-1$

Table S2 – Transformation applied for the decay rate analysis. OD stands for Ocular Dominance.

Supplementary results: quantitative analyses

Supplementary Figure 1-5 gives a forest plot with all datasets contributing to the analysis in Figure 1-1 (short-term monocular deprivation studies). They are listed in chronological order, with some publications reporting more than one dataset; each is accompanied with its effect-size estimate, standard error and 95% confidence interval. Datasets where the confidence interval straddles the x=0 line, implying a non-significant effect, are also marked with black crosses in Figure 1-1.

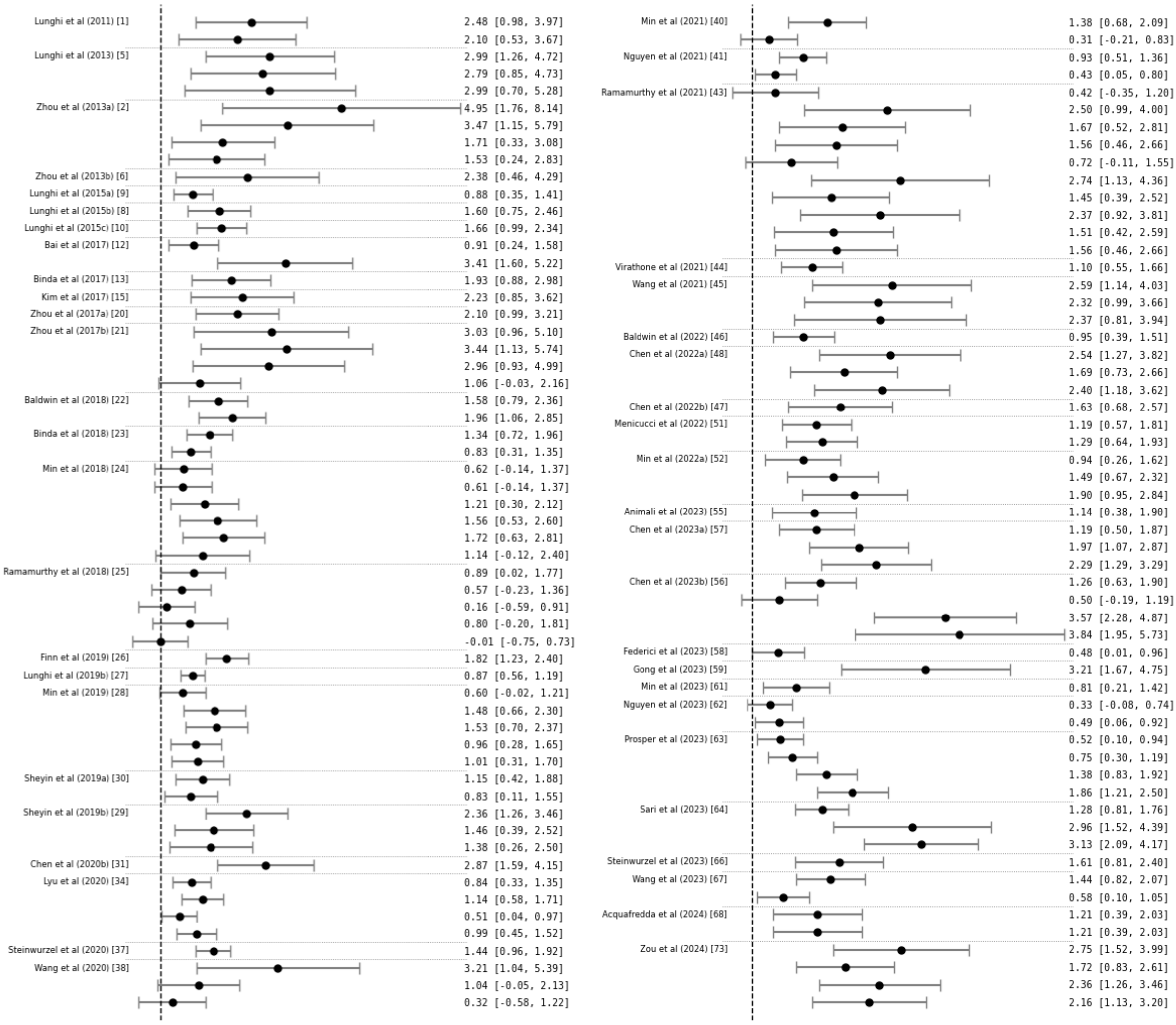

Figure 1-5 *Forest plot of the effects of short-term monocular deprivation. The leftmost column reports the first author and year for each publication, values in square brackets represent the corresponding number in the reference list. The rightmost column reports effects sizes and 95% confidence intervals. The vertical dotted line corresponds to effect size = 0.*

Supplementary Figure 1-6 illustrates two representative decay curves extracted from the same study [52], which monitored the ocular dominance shift at multiple points after patch removal, for two deprivation durations: 30 minutes and 5 hours. Data-points were expressed as percentages of the effect observed immediately after patch removal (i.e. by definition the first time-point is 100%).

Distributions were fit with exponential functions of the form $y = a^x + b$, where a and b were free parameters; text insets give the goodness of fit (computed as variance explained or adjusted R^2) and the estimated percentage of the effect that was still measurable 30 minutes after patch removal. This value was extracted from all decay curves and studied as function of deprivation duration in Figure 1-2B of the main text.

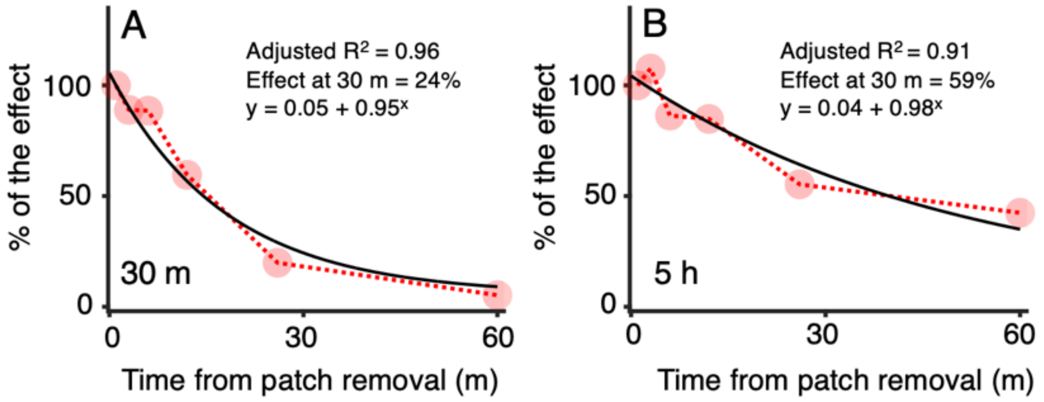

Figure 1-6 *Examples decay curves, showing the percentage of ocular dominance shift. Filled dots represent single timepoint after patch removal. The black solid lines represent the best fit exponential function.*

Note that the decay rate analysis presented in Figure 1-2B of the main text is conceptually independent from that in Figure 1-2A, given the evidence that decay rate can vary independently of the effect size. For example, short-term monocular deprivation using colored binocular rivalry stimuli led to an estimated effect that had about the same size as with achromatic grating but lasted way longer (after 30 minutes there was still a 64% of the initial effect for colored gratings, compared to 7% for achromatic gratings) without altering the peak effect [5]. On the other hand, physical activity [10] can increase the peak effect without altering its decay (the residual effect at 30 minutes was 55% and 60% with and without physical activity).

Supplementary Figure 1-7 shows the distribution of effect sizes across datasets where short-term monocular deprivation was achieved with a light-tight or translucent patch, on the dominant or non-dominant eye. Neither factor reliably influenced the size of the effect.

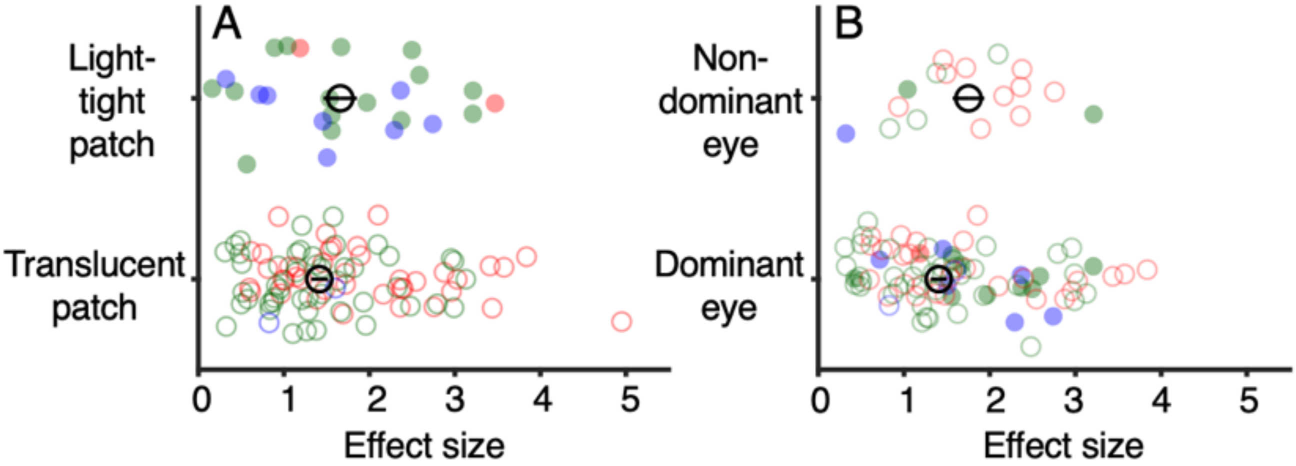

Figure 1-7 *Effects of monocular deprivation on ocular dominance (x-axis) shown separately depending on patch type (A) or patched eye (B). For both panels, filled dots represent experiments with light-tight patch and empty circles those with translucent patch (or contrast nulling in dichoptic viewing). Different colors represent the three categories of techniques represented in Figure 1-1 (same color coding: red for binocular cooperation techniques, green for binocular competition techniques, and blue for monocular techniques). Black circles show the mean and s.e. of the effect in each subgroup of datasets.*

Supplementary results: quality assessment, sensitivity analysis, publication bias

Formal quality scoring tools (e.g. Cochrane Risk of Bias) are typically designed for clinical trials and hard to apply to our investigation. However, we applied a similar logic for the following assessment. First, we considered sample sizes of the analysed studies; after excluding studies with less than 4 participants, the average sample size was 12, representing a medium-to-large sample in psychophysical studies involving normally sighted healthy participants. Second, all analysed datasets were characterized by high method appropriateness, as they were all generated with established psychophysical techniques. Third, transparency of reporting is generally very high given that all analysed datasets reported very standard psychophysical indices, from which extracted a single variable: ocular dominance.

Sensitivity analyses were conducted to test the robustness of our main results. An influence analysis identified two studies with exceptionally large effect sizes and sample sizes [56, 64]. When we excluded these, the results of the model remained highly significant ($k = 112$; estimate $= 1.3$; $z = 20.7$, $p < 0.0001$). We also implemented a leave-one-out analysis, testing the effect of removing each study from the analysed dataset; overall effect size always remained highly significant (all $p < 0.001$).

Potential publication bias was assessed by examining the relationship between effect size and publication year or sample size (trough a mixed-effects model, described in the Methods of the main text) and with a funnel plot, reporting effect size against an estimate of standard errors computed with the same equation used for the forest plot. These plots are shown in Supplementary Figure 1-8, and the relevant statistics are reported in the main text.

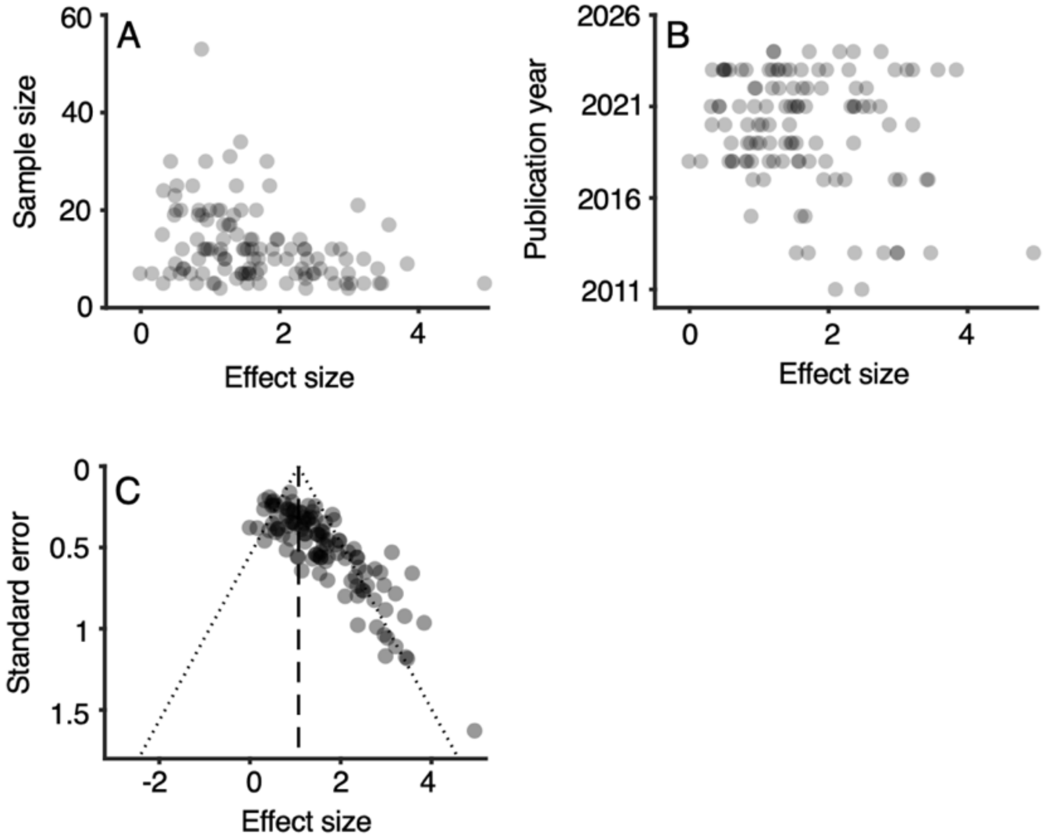

Figure 1-8 *Effects of monocular deprivation on ocular dominance (x-axis) shown separately against sample size (A), publication year (B) or estimated standard errors (C), the latter resulting in a funnel plot. Each dot represents one dataset. The vertical dotted line in C represents the average effect size, and the diagonal lines present its confidence intervals.*

Supplementary results: quantitative analyses for other monocular manipulations

Supplementary Figure 1-9 gives a forest plot with all datasets contributing to the analysis in Figure 1-3 (other short-term monocular manipulation studies).

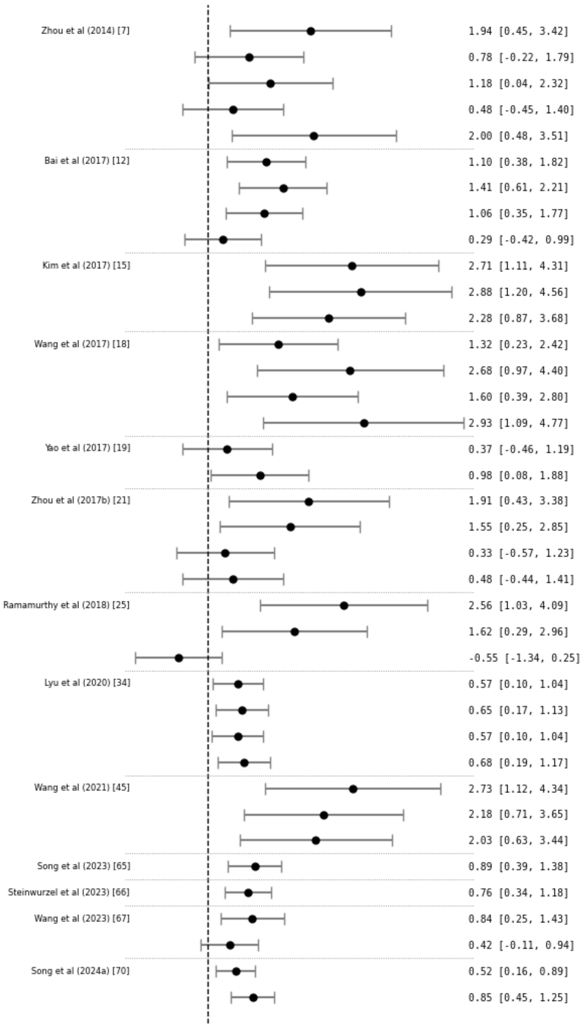

Figure 1-9 *Forest plot for other short-term monocular manipulations. Conventions are the same as for Supplementary Figure 1-5*

Supplementary results: qualitative analyses

Binocular techniques

Binocular techniques afford a direct index of ocular dominance. This may be estimated in two ways: by presenting incoherent stimuli in the two eyes and testing how they are mutually suppressed (which we dub “binocular competition” tests) or by presenting relatively coherent stimuli in the two eyes and testing how they cooperate to support task performance (we refer to these as “binocular cooperation” tests).

Among the binocular competition techniques, binocular rivalry was used in the first study [1] and in many subsequent ones. In binocular rivalry, two incompatible images are presented to the two eyes and perception alternates between seeing through either eye or (more rarely) a combination of the two, the so-called mixed percepts. The effect of monocular deprivation (and other monocular manipulations) consists of an increased proportion of time spent seeing through the manipulated eye, and an increase of the manipulated eye mean phase duration. Min et al. [40] suggested that binocular rivalry has lower reliability than other binocular cooperation tasks and it is less effective for revealing the effects of monocular deprivation; however, inspection of Figure 1-1 suggests that the average effect size for binocular rivalry is above 1, more than four times larger than the effect size considered in [40]. A variation of the binocular rivalry technique is onset rivalry, measuring only the first phase of binocular rivalry, which is reliably biased towards the deprived eye after monocular deprivation [1, 41, 44, 62, 72] – possibly a larger effect than the ocular dominance shift computed from an extended period of rivalry [1, 41].

A related technique is continuous flash suppression, where one eye is presented with a dynamic, salient stimulus that steadily dominates over the less salient static image presented to the other eye; the contrast of the suppressed stimulus is increased until it "breaks suppression". Monocular deprivation decreases the contrast increment required for the deprived eye to break suppression [38], consistent with enhanced sensitivity in the deprived vs. non-deprived eye. The measures achieved by dichoptic masking are conceptually similar, as these techniques measure the sensitivity in one eye (e.g., the deprived eye) as a function of the presence and contrast of an interfering "mask" stimulus in the other eye. Masks generally elevate monocular detection thresholds; the effect of a mask in the non-deprived eye was reduced after monocular deprivation [22, 59]. In a similar experiment, the mask consisted of an annulus surrounding the target stimulus; target and mask were again presented in separate eyes (the deprived and non-deprived eye respectively), producing a dichoptic surround suppression effect, which was reduced after deprivation [46] and after a more complex monocular manipulation [33]. Finally, in the dichoptic global motion coherence task, the two eyes are presented with dots, some coherently moving in one direction (presented to the deprived eye), others moving randomly (presented to the non-deprived eye). The random motion in the non-deprived eye interferes with the detection of coherent motion; after monocular deprivation, this interference was reduced [2, 25, 43], once again consistent with enhanced dominance of the deprived eye over the non-deprived eye.

Studies using dichoptic frequency tagging with Electro- [11, 67, 70] or Magneto-EncephaloGraphy [14] reached similar conclusions. In this approach, the two eyes are shown with incongruent stimuli (e.g. orthogonal gratings) that flicker at different frequencies; the Fourier spectrum of the EEG or MEG signal is dominated by the first harmonics of both frequencies, and their amplitudes measure the contribution of the two eyes to the steady-state visual evoked response. The ratio between responses in the two eyes was shifted in favor of the manipulated eye, both following monocular deprivation [11, 14, 67] and more complex manipulations [70]. The two studies that analyzed the modulation separately for each eye reported a selective enhancement of the deprived eye with no reliable modulation of the non-deprived eye [11, 14]. Acquafredda et al. [68] explored how pupillometry can serve as an objective physiological marker of ocular dominance plasticity by measuring pupil diameter during binocular rivalry before and after short-term monocular deprivation; they found an increase in the amplitude of these pupil-size modulations after deprivation – with no change in absolute pupil diameter, suggesting that the effects were not due to general retinal adaptation or changes in luminance sensitivity.

Among the cooperation techniques, binocular phase combination was the most common. The two eyes are shown with similar, though not identical stimuli, e.g. gratings with slightly different orientation or phase; the task is to report the phase or orientation of the single percept resulting from the fusion of the two images. Monocular deprivation increased the weight of the deprived eye stimulus in the fused percept. Like for binocular rivalry, stimuli can either be chromatic or achromatic. While most studies used achromatic stimuli, Zhou et al. [21] directly compared the effects measured with a/chromatic stimuli and found them indistinguishable; the same comparison with binocular rivalry revealed a difference in the dynamics of the effect [5], suggesting that the two techniques might measure different aspects of the monocular deprivation effect [12, 63]. A related implementation is the dichoptic tilted edges task [17], where the two eyes are presented with blurred edges of varying stimulus disparity and contrast. Participants report whether they perceive a single flat edge (indicating fusion), a single tilted edge (indicating dominance of one of the two monocular images and suppression of the other), or two tilted edges (indicating diplopia). While the probability of fusion and diplopia were unaffected by deprivation, the deprived eye image tended to dominate perception, suppressing the non-deprived eye. An alternative approach is the binocular contrast matching task [2], where the two eyes are presented with gratings of identical phase and orientation, but different contrast. The perceived contrast of the fused percept is intermediate between the two monocular images, as may be appreciated by matching it with a monocular grating of variable contrast presented in the deprived eye. A simpler variant of this task requires participants to match the contrast of two monocular stimuli presented at abutting locations [1]. In both cases, monocular deprivation shifted contrast matches indicating that the deprived eye required less contrast to match the stimulus in the non-deprived eye [1, 2].

Similarly, in the dichoptic letter polarity test [47, 56] each eye saw two letters, one white the other black and the contrast polarity of the letters is swapped across eyes. Participants reported which letter appeared brighter, indicating dominance of the eye that was presented with the white version of that letter. Monocular deprivation increased the proportion of trials where the letter presented in white to the deprived eye was chosen, once again indicating enhanced dominance of the deprived eye.

Two EEG study applied a binocular frequency tagging approach [34, 65], similar in all respects to the dichoptic frequency tagging described above but using congruent stimuli in the two eyes, that are readily fused despite their different flicker frequency. Results were reported as deprived/non-deprived eye response ratios (i.e. the ratios of the Fourier amplitudes at the harmonics of the corresponding stimuli, measured from occipital electrodes), which was shifted in favor of the manipulated eye following monocular deprivation [34] and a more complex monocular manipulation [65]. In a conceptually similar approach [36], both eyes are presented with a luminance patch of variable intensity, uncorrelated between eyes. Correlating the EEG signal from occipital electrodes to each temporal series allows for estimating the impulse response function for each eye. Its peak amplitude measures the contribution of each eye to the evoked response, which was enhanced for the deprived eye and suppressed for the non-deprived eye. Another parameter of the impulse response function is the oscillatory pattern observed after the initial peak; this echo response is dominated by an alpha rhythm, associated with perceptual sampling. In contrast with the modulation of visual evoked responses, the same dataset revealed no significant alpha modulation in the echo response – though the deprived eye amplitude was numerically larger after vs. before deprivation.

Monocular techniques

Monocular techniques measure sensitivity in the two eyes separately; these may be combined to compute an ocular dominance index, under the key assumption that enhanced monocular sensitivity implies enhanced dominance.

Studies measuring monocular contrast sensitivity provided partially conflicting results, potentially related to differences in the type of patch (translucent vs. light-tight). In three studies [2, 21, 60], application of a translucent patch was found to enhance sensitivity in the deprived eye (two of these also tested the non-deprived eye and found impaired sensitivity [2, 21]), while no modulation of deprived eye sensitivity was observed in Lunghi et al. [1]. Where the whole contrast-sensitivity function was measured, a preferential enhancement of the higher spatial frequencies was revealed [60] – but no sensitivity modulation was observed when stimuli were embedded in noise. Another four studies [25, 38, 43, 57] tested the effects of a light-tight monocular patch, which primarily impaired sensitivity in the non-deprived eye (seen in three out of four studies), with only a marginal enhancement of sensitivity in the deprived eye (only observed in [25]). Similar modulations were observed for a more complex monocular manipulation [25]. The one study that failed to report a sensitivity modulation [38] measured contrast-discrimination thresholds rather than absolute thresholds, i.e. participants' ability to report a contrast difference between two halves of a suprathreshold (clearly visible) grating. Another null finding came from monocular global motion coherence thresholds [25], which did not change following the application of an opaque patch (in contrast with the results of dichoptic global motion coherence) indicating that monocular sensitivity to motion is not affected by deprivation.

Few studies used EEG or fMRI to study the amplitude of responses evoked by monocular stimulation [8, 11, 23, 49, 58]; all achieved monocular deprivation through the application of a translucent patch. Lunghi et al. [8] used EEG to measure the event related potentials for individual stimulus presentations and found that deprivation modulates the amplitude of the earliest component of visual evoked potentials, known as C1. This was enhanced for the deprived eye and suppressed for the non-deprived eye. Federici et al. [58] replicated the C1 modulation; in addition, they quantified the spectral composition of EEG oscillations induced by stimulation. These consist of oscillations that are neither time- nor phase-locked to the stimulus onset, yet they are induced by the stimulation and modulated by its content. After monocular deprivation, alpha oscillations induced by deprived eye stimulation were reduced. Assuming that induced alpha is associated with inhibition, the modulation was interpreted as enhanced excitability, consistent with the modulations of evoked responses. Zhou et al. [11] measured steady-state evoked potentials, extracting the Fourier amplitude of the occipital EEG signal at the first harmonic of the monocular stimulus frequency. The results showed a selective enhancement of the deprived eye response, with no corresponding suppression of the non-deprived eye. Using ultra-high field functional MRI, Binda et al. [23] measured evoked BOLD responses in the primary visual cortex and Kurzawski et al. [49] extended the analyses to the visual thalamus. The results showed enhanced deprived eye responses and suppressed non-deprived eye responses in the primary visual cortex, particularly for the higher spatial frequencies tested, but no modulation in the lateral geniculate nucleus, supporting a cortical origin of the effect. However, a reliable modulation of evoked responses was observed in the ventral pulvinar.

Other techniques and indices

In our meta-analysis, we only considered studies that tested the effects of monocular deprivation on ocular dominance; here we describe experiments that considered other aspects of perception or resting state physiology.

The same binocular tasks that measure ocular dominance also give indices of binocular fusion (or lack thereof, i.e. diplopia). Of the 20 experiments that reported such indices, 16 found no change [1, 5, 12, 17, 25-27, 37, 44, 45, 47, 55, 56, 62, 63, 68]; three found increased probability of mixed percepts after monocular deprivation [30, 41, 71] and one reported decreased mixed percepts [34]. These statistics suggest that binocular fusion is not strongly affected by deprivation. A separate set of tasks measured temporal vision and found that resolution is unaffected by monocular deprivation [32] (in partial contrast with the seminal work by Zubek [74, 75]); however, there was a slight delay (by few milliseconds) of the deprived eye relative to the non-deprived eye revealed through the Pulfrich effect [42, 53]). Three studies asked whether, besides changing monocular responses and binocular vision, monocular deprivation also affects the integration of visual and non-visual signals. Different results were obtained for different integration tasks. On the one hand, the temporal binding window for visual and auditory events was enlarged for the deprived eye, suggesting enhanced audio-visual integration [35] (although this was insufficient to affect the sound-flash illusion [58]); on the other hand, visuo-haptic integration during rivalry was impaired for the deprived eye, suggesting that monocular deprivation reduces our ability to integrate information across senses [16].

Finally, five studies measured how monocular deprivation affects resting state physiology. Occipital resting state functional connectivity measured with fMRI is clearly affected [76] and so are alpha rhythms are clearly affected; induced alpha during stimulation of deprived eye was reduced [58] and resting alpha during pauses between deprived eye stimulations enhanced [8]. Combined with the observation that GABA concentrations in primary visual cortex are reduced after monocular deprivation [9], these results provide strong indications that monocular deprivation is linked with enhanced cortical excitability (see also above). One apparent contradiction is with an early TMS study, which reported decreased probability of phosphene generation during application of a monocular light-tight patch [3]; however, it is unclear whether the conditions of this study are entirely comparable with the rest of the meta-analyzed studies.

Pupillometry was also employed to measure changes of the resting-state physiology across monocular deprivation. This study revealed that a slow rhythm (<1 Hz), termed "hippus" and related to the balance of autonomous nervous signals, is reliably enhanced following monocular deprivation [13].

One final study investigated the impact of monocular deprivation on perceptual learning. Shibata et al. [4] applied monocular deprivation continuously for three days and reported an acceleration of learning for the non-deprived eye – suggesting that monocular deprivation may promote our ability to learn from the environment.

In summary, studies that did not look at ocular dominance applied a heterogenous set of techniques and produced partially conflicting results. However, they have the important merit of showing the complexity of monocular deprivation effects, which likely extend beyond a gain modulation of visually evoked responses.

Concluding Remarks

In our meta-analysis, 16 out of 114 datasets showed a non-significant ocular dominance shift. These null results were obtained with similar techniques and approaches as studies with positive results. Importantly, no dataset reported a statistically significant shift in the opposite direction – in favor of the *non*-deprived eye. To our knowledge, the one exception is Qian et al., 2025 [77] (published after the completion of our meta-analysis), where the balance between monocular responses measured with fMRI was evaluated at multiple stages of the visual hierarchy; the results indicate a shift in favor of the non-deprived eye, but this is selectively observed in higher-level areas, suggesting that it might be a secondary e.g., compensatory effect.

From the synthesis of the literature, two main factors reliably influence the characteristics of the short-term monocular deprivation effect:

- **Deprivation duration**: this is the most robust modulator identified (accounting for 10.2% of heterogeneity). Longer deprivations produce larger and longer-lasting effects, following a saturation function with a ceiling around 5 hours.
- **Technique used for monitoring ocular dominance**: depending on the duration of the task and its test-retest reliability, some techniques are more suitable for revealing the short-term monocular deprivation effects.

In addition, the following produced subtler modulations:

- **Dark exposure prior to deprivation**: one hour of total darkness before the session enhances the effect, likely through an increase in cortical excitability.
- **Time of the day**: the effect is larger when deprivation is performed in the morning compared to late evening.
- **Metabolic state**: having a standardized breakfast before deprivation produces a larger effect compared to prolonged overnight fasting, a result consistent with modulation of cortical excitability through energy metabolism.
- **Visually guided goal-directed actions**: as it will be demonstrated in Chapters 2 and 3, performing manual goal-directed actions during deprivation or during monocular delay significantly enhances the plasticity effect.

- **Keeping the deprived eye shut** under the patch produces a smaller effect.
- **Reducing visual information in the non-deprived eye**: when the open eye is also exposed to impoverished stimuli (a uniform curtain), the effect disappears.

In contrast, the following factors did not modulate the magnitude of the effect:

- **Patch type** (opaque vs. translucent).
- **Patching the dominant vs. non-dominant eye** produced similar effects.
- **Publication year**: there is no significant bias for larger effects reported in earlier studies.
- **Age**: the effect is comparable across adolescents, young adults, and older participants.
- **Sex/gender**: no associations reported.
- **Non-invasive stimulation of the occipital cortex** during deprivation: no effect.

References

[1-73] *See references in the main text*

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CHAPTER 2:

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Prefatory Note

The present chapter reproduces the published manuscript with editorial adaptations to ensure coherence across the thesis. Introductory sections overlapping with earlier chapters have been condensed or replaced with cross-references to maintain continuity while preserving the integrity of the original article.

Monocular delay during visually guided actions is as effective as monocular deprivation in driving ocular dominance plasticity

Introduction

As detailed in Chapter 1, short-term monocular deprivation in adult humans produces a paradoxical shift of ocular dominance in favor of the deprived eye and has been widely interpreted as a form of homeostatic plasticity [1-14].

However, we recently demonstrated that reducing the sensory input to one eye is not necessary to induce the short-term ocular dominance shift [15]. We used an altered-reality setup to delay the visual input in one eye by 333 ms while participants continuously performed visually-guided goal-directed actions (building towers with wooden blocks) for one hour. At the end of this period of monocular delay, ocular dominance shifted towards the delayed eye, qualitatively reproducing the shift of ocular dominance towards the deprived eye elicited by monocular deprivation.

This result aligns with previous evidence that a short-term ocular dominance shift can be elicited by manipulating the input in one eye (without attenuating it): through temporal reversal of a visual sequence [16-18], application of an inverting prism [19], phase scrambling [20-23] or application of a kaleidoscopic lens [24]. In all cases, ocular dominance shifted in favor of the manipulated eye. These manipulations share a key feature: they make the input in the two eyes incompatible, inevitably discouraging binocular fusion and likely promoting perceptual suppression of the distorted/inverted eye. It is possible that such inter-ocular suppression mimicked the effects of the physical removal of input to the same eye [16-18, 25], hence reproducing the post-deprivation homeostatic boost. Our approach differed from these paradigms in two important ways. First, our monocular delay only introduced sparse and local mismatches between the eyes: only at the spatiotemporal coordinates of moving objects did dichoptic vision become incongruent, while all static elements in the scene remained congruent promoting binocular fusion. Second, monocular delay alone did not promote any ocular dominance shift, indicating that our manipulation of the visual input was not responsible for the effect. The ocular dominance shift was only observed when monocular delay was paired with active engagement in a visually-guided goal-directed series of actions; it was not observed when participants passively viewed (with the same monocular delay) someone else performing the task. This result is indicative of the importance of visually-guided goal-directed actions (with the associated motor, perceptual and cognitive effects) for the generation of the ocular dominance shift.

There are multiple classically described mechanisms through which actions could modulate visual perception. One is through the feedback signals generated by action execution, e.g. through integration of proprioceptive signals generated by the action [26]. Another is through a "corollary discharge" or "efference copy" signal, which is generated in-synch with the motor command and sent to the sensory systems to predict the consequences of the action and eliminate them from awareness (e.g. the retinal motion generated during a saccadic eye movement [27-29]). This view implies that actions may be encoded as complex representations, which include their consequences on the external world and the agents themselves [30]. Action planning and execution are also inextricably linked with shifts of covert attention, which focus processing resources at the spatio-temporal coordinates that are most relevant for the action [31]. That plasticity was selectively elicited when monocular delay was combined with goal-directed actions, not in passive viewing conditions, suggests that any of these mechanisms (or all of them) contributes to gating the short-term ocular dominance shift.

One important limitation of our previous study [15] consists in the imperfect control of the passive viewing conditions. The visual input during the passive control was not the same as during visually-guided actions, because actions in the two conditions were performed by different agents at different times. This difference could in principle be responsible for the different results in the active vs. passive conditions. The first aim of the present study was to exclude this possibility, by ensuring that visual stimulation was identical across the two conditions. For this, we recorded each participant's binocular view while they performed the tower-building task with the 333 ms monocular delay [15], and then replayed the same binocular visual input to the same participant, who passively watched the scene in first-person perspective (promoting sense of agency [32]). We asked whether the ocular dominance shift induced by monocular delay would still be larger during goal-directed actions than in passive viewing, even though visual stimulation was identical across conditions.

With the present study, we also pursued a second aim, to evaluate the magnitude of the ocular dominance shift induced by monocular delay during goal-directed actions, compared with the effect induced by monocular deprivation. To measure both effects in comparable conditions, we presented the same participants with another replay of their own actions, but this time we only showed the image in the non-delayed eye, while the other was replaced with a static homogeneous gray screen. This allowed us to directly compare the effects of monocular deprivation (nulling contrast in one eye) and those of monocular delay, with these two conditions applied for the same one-hour period and with the same visual stimulation of the non-manipulated eye – two of the main factors affecting the monocular deprivation effect-size (duration [33,34]; visual experience during the experimental condition [15,19,35]; as reviewed in [7]).

Methods

Human participants

Experimental procedures were approved by the regional ethics committee [Comitato Etico Pediatrico Regionale - Azienda Ospedaliero-Universitaria Meyer - Firenze (FI); protocol "Plasticita' del Sistema visivo"] and are in line with the principles of the declaration of Helsinki. Participants gave written informed consent before participating in the studies. We estimated the necessary sample size based on our previous study [15]; we took the difference between ΔOD% (ocular dominance shift measured with proportions, see Eq. 1 below) in the condition where participants actively engaged in the tower building task vs. passively viewed another person performing the task. The Cohen's d of this difference indicated a large effect size (d = 0.9); we computed the number of participants required to replicate such effect with 80% power and alpha 0.05, yielding 12 participants.

We recruited 21 participants, all with normal or corrected-to-normal vision, with no history of amblyopia, strabismus, or eye surgery. Two participants were excluded due to difficulty in following the instructions (they failed to maintain continuous activity on the tower-building tasks, frequently pausing the task despite being urged not to). Nineteen participants took part in the active monocular delay condition; a subset of these also took part in the monocular deprivation (N=15) or the passive monocular delay conditions (N=15). Fourteen participants completed all three conditions.

In 14 participants, we verified the quality of stereovision with the Firsby Stereotest™; they had a mean stereoacuity of 107 (s.e.m. = 3) seconds of arc. For all participants the dominant eye was assessed by binocular rivalry (see below, "Binocular Rivalry" section).

Altered-reality set-up

Participants sat at a desk with a 37 x 29 cm area containing wooden bricks that they could manipulate; the working area was comfortably within their arm range (20 to 60 cm from the participant's head). Participants viewed the desk area and their hands through an Oculus VR headset (Oculus Rift, DK2, fit to the headrest) displaying the images captured with a stereo camera (Zed) mounted upon the Oculus frame (Figure 2-1). Participants' head and the Oculus set were stabilized with a chin and headrest, minimizing the sense of discomfort and nausea that is typically reported when the Oculus set was used head-free.

The combined stereo camera and Oculus VR system had a visual field of 80 x 60 deg with a resolution of 960 x 720 pixels per eye. Camera vergence was adjusted for each participant to account for small differences in interpupillary distance. The Zed camera and Oculus system had refresh rates of 60 Hz and 75 Hz respectively, and a minimum delay of 35 ms. In the main experiment, participants engaged in a visuomotor task, using wooden bricks (average size: 2 cm) to build block-towers continuously for one hour, with visual information conveyed through the altered-reality set-up. They were instructed to construct as many and as tall towers as possible, rebuilding them when they collapsed. We recorded the images streamed on the altered-reality set-up, capturing participants' activities with a first-person perspective; the recording was achieved through the same integrated software that operated the altered-reality system. Sounds were not recorded.

In two participants, we additionally acquired an image of the eye, to ensure that participants kept them open throughout the experiment. We quantified the percentage of time during which one eye was closed (e.g. due to blinks); this was less than 5% on average, stable over the course of the one-hour experiment.

Experimental procedure

Participants were tested in three sessions, each lasting one hour and conducted on separate days, with binocular rivalry assessed at the beginning and the end of each session.

In the first condition, participants engaged in a visuomotor task while their dominant eye vision was delayed by 333ms (ocular dominance was determined with binocular rivalry, see below). The delay produced large interocular differences for any moving object including their hands. Participants reported seeing the moving object twice or seeing a moving object with a tail or shadow trailing behind it. However, this was selective for the visual field regions containing visual motion. For all other regions (>80% of pixels), the two binocular images were fused.

In the other two conditions (monocular delay in passive viewing and monocular deprivation), participants watched a replay of their own recorded activity through the same altered-reality set-up with the dominant eye delayed by 333 ms or substituted with a homogeneous gray screen. In both conditions, participants passively re-viewed the scene without engaging in any task (Figure 2-1); in both cases, only the video was re-played, without sounds.

Binocular rivalry

Before and after the 1h exposure to monocular delay or monocular deprivation participants quickly removed the Oculus VR set and turned to an adjacent apparatus for measuring binocular rivalry and estimating ocular dominance. We used two different set-ups to assess binocular rivalry, one using Ferro-Magnetic shutter goggles, the other using a mirror stereoscope. For the first set-up, a ViSaGe (Cambridge Research Systems) housed in a PC (Asus) controlled by MATLAB (MATLAB r2010a, The MathWorks) generated and displayed the stimuli on a linearized monitor (Barco CDCT, 800 x 600 pixels) driven at 100 Hz, synchronized with the Ferro-Magnetic shutter goggles (Cambridge Research Systems). For the mirror stereoscope set-up, stimuli were generated with the Psycho-Toolbox routines [53,54] for MATLAB (MATLAB r2010a, The MathWorks) housed in Mac PC and displayed on a linearized monitor (Display ++, CRS, Cambridge Research Systems, 1920 x 1080 pixels) driven a 120 Hz. In both set-ups, participants viewed the display at a distance of 57 cm with a chinrest stabilizing head position. Binocular rivalry stimuli were two orthogonal sinusoidal gratings (orientation: ±45°, spatial frequency: 2 cycles per degree), Gaussian-vignetted within a s = 2.5 deg window. Gratings were presented against a mean luminance background (5.85 cd/m2); they were overlayed with a central black fixation point and framed by a black square, both presented binocularly to facilitate fusion.

The stimulus was delivered in periods of 180 seconds, during which participants reported perceptual oscillations by holding down one of three keys to indicate: dominance of the clockwise grating, dominance of the counterclockwise grating, or mixed perception (fusion or piecemeal combination of the two gratings). Four periods of stimulation (about 12 minutes) were tested both before and after the 1h exposure to monocular delay; the assignment of the two grating orientations to the left and right eye was swapped across periods. 12 minutes represents a compromise between collecting enough data to reliably assess the ocular dominance shift and measuring the effect before it exponentially decays back to baseline [55].

For the analysis, we averaged across the second, third and fourth periods; we excluded the first period to ensure data homogeneity, as it typically exhibits stronger but also more variable effects across participants. Due to a failure in data storage, one participant only had two periods of stimulation for the baseline measurements of one session, and we averaged across the two available periods.

We quantified binocular rivalry dynamics by analyzing the duration of dominance phases (periods of time where either eye dominated perception) and by computing the percentage of dominance time spent seeing through one eye (Equation 1).

$$OD = 100 * \frac{TimeDE}{TimeDE + TimeNDE} \qquad \text{(Equation 1)}$$

where DE stands for Dominant Eye and NDE stands for Non-dominant Eye. We marked one eye as dominant (preOD > 50%) with a preliminary binocular rivalry session. We quantified the effect of each experimental condition by taking the the difference between ocular dominance indices calculated before and after each experiment (ΔOD% = postOD% - preOD%).

For completeness, we also computed the percentage of total testing time spent seeing mixed percepts (i.e. incomplete dominance of either eye), and compared before and after each experiment.

Results

We used a custom-built altered-reality set-up to control binocular visual stimulation. In the main experiment, participants (N=19) performed goal-directed actions under visual guidance (they used wooden blocks to build towers), while the altered-reality set-up delayed the input to their dominant eye by 333 ms (Figure 2-1). We consistently applied monocular delay to each participant’s dominant eye, like in our previous study [15] and following a common practice in short-term monocular deprivation studies [7]. The tower-building task lasted one hour, during which the visual input to the two eyes was recorded. We then replayed the video to two subsets of the same participants (both N=15), who watched it passively in two comparison conditions (approximately two weeks apart): in the first, the two monocular images were both delivered to the corresponding eyes, reproducing the same visual stimulation as in the main experiment including the monocular delay; in the second condition, the delayed image was replaced with a homogeneous gray screen, inducing a form of monocular deprivation.

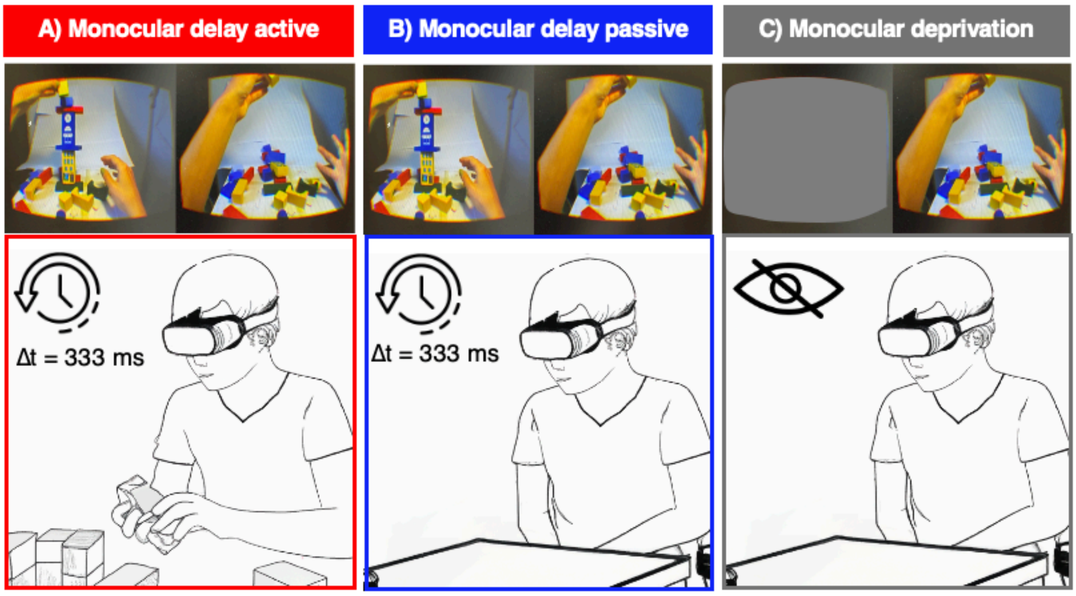

Figure 2-1 *Experimental set-up for the three monocular conditions. A) Monocular delay during visually-guided goal-directed actions, during which participants built towers with wooden blocks, monitoring their actions through an altered-reality set-up (stereo-camera mounted above an Oculus set); the image in their dominant eye was delayed by 333 ms. B) Monocular delay in passive viewing, where participants passively watched a replay of the images recorded in A, including the delayed image in their dominant eye. C) Monocular deprivation: participants passively watched a replay of the images recorded in A except the image in their dominant eye was replaced with a homogeneous gray screen. Each condition lasted one hour, preceded and followed by binocular rivalry tests that measured ocular dominance. The active condition was always tested first; its*

recordings were used in the other two conditions, the order of which was counterbalanced across participants.

Immediately before and after each one-hour experiment, ocular dominance was assessed with binocular rivalry. Ocular dominance may be quantified with two binocular rivalry parameters: dominance proportions and mean dominance phase durations.

Dominance proportion is defined as the total time during which the image in the dominant eye was perceived, divided by the total dominance time (i.e. the total testing time minus the short intervals during which perception was a mixture of the stimuli in the two eyes) and expressed as percentage.

Figure 2-2 shows the dominance difference (ΔOD%) after vs. before each one-hour experiment. A one-way ANOVA considering the 14 participants tested in all three conditions revealed a significant effect of conditions (F(2,26) = 5.45, p = 0.011, $h_p^2 = 0.29$)

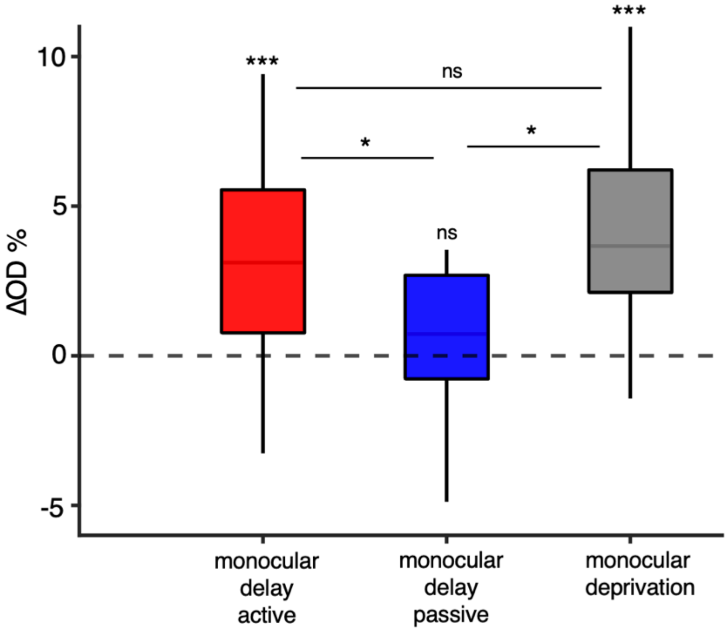

Figure 2-2 *Shifts of ocular dominance (ΔOD%, defined as the dominance proportion of the manipulated eye, measured after each one-hour experiment, minus the dominance measured before the experiment) elicited in the three monocular conditions. The dashed line at y = 0 indicates no effect. The box plots show the median, interquartile and range of the three distributions (same color coding as in Figure 2-1) for all participants tested in each condition (19, 15 and 15 respectively);*

*symbols above each distribution report the significance of each distribution (***$p<0.001$, ns = not significant). The ANOVA and the post-hoc tests (symbols above horizontal lines, *$p<0.05$, **$p < 0.01$, ns = not significant, Bonferroni corrected) were run on the subset of N = 14 participants with data in all conditions.*

Follow-up post-hoc t-tests (Bonferroni corrected) compared the three conditions, showing a significant difference between the *monocular delay during visually-guided goal-directed actions* and *the monocular delay during passive viewing* conditions (post-hoc t-test, t(26) = 2.59, p = 0.046, logBF = 0.42), as well as between the *monocular delay during passive viewing* and the *monocular deprivation* conditions (post-hoc t-test, t(26) = 3.06, p = 0.015, logBF = 0.45). In contrast, there was no significant difference between the *monocular delay during visually-guided goal-directed actions* and *monocular deprivation* (post-hoc t-test, t(26) = 0.47, p = 1, logBF = -0.48). We also performed one-sample t-tests on the three ΔOD% values (considering all participants tested in each condition), which showed significant effects in both the monocular delay during *visually-guided goal-directed* actions ($t(18) = 4.19$, $p < 0.001$, logBF = 1.79) and the monocular deprivation conditions ($t(14) = 5.21$, $p < 0.001$, logBF = 2.35), and no significant effect of monocular delay during passive viewing ($t(14) = 1.17$, $p = 0.258$, logBF = -0.32).

Figure 2-3 shows an alternative metrics based on mean phase durations, which are commonly used to characterize rivalry dynamics[36] and can provide an indirect index of ocular dominance, with longer mean phase durations associated with the dominant eye vs. the non-dominant eye. Dominance phases are time-intervals during which perception is dominated by the image presented in one eye, before switching to the image presented in the other eye (or to a mixture of the two). We studied mean phase durations across time-points (before vs. after the 1h experiment) and eyes (dominant vs. non-dominant) for the three conditions of our experiment (monocular delay during visually-guided goal-directed actions, monocular delay during passive viewing and monocular deprivation); we entered these values a three-way ANOVA for repeated measures after log-transforming the values. This revealed a significant main effect of *eye* (dominant vs. non dominant: F(2,26) = 25.98, p < 0.001, ηp² = 0.66) meaning that, as expected, dominance phases lasted longer for the dominant eye than for the non-dominant eye. This dominance was modulated over time (significant *eye* × *time* interaction: F(2,26) = 13.62, p = 0.003, ηp² = 0.51), suggesting that ocular dominance shifted between the pre- and post-experiment phases. With one exception, the other main effects or interactions were far from the significance threshold (*condition*: F(2,26) = 2.20, p = 0.13, ηp² = 0.14; *time*: F(2,26) = 1.80, p = 0.20, ηp² = 0.12; *condition* × *time*: F(2,26) = 0.68, p = 0.51, ηp² = 0.05; *condition* × *eye*: F(2,26) = 0.53, p = 0.59, ηp² = 0.04; see also Supplementary Materials for two-way ANOVAs on data from each condition). The exception was the three-way interaction, which revealed a non-significant trend for ocular dominance shifts to vary across conditions (*eye* × *time* × *condition:* F(2,26) = 2.78, p = 0.08, ηp² = 0.17). This trend is qualitatively consistent with the effect revealed by analyzing the proportion-based ocular dominance index in Figure 2-2; its non-significance is likely related to the lower reliability of ocular dominance estimates based on mean phase durations, compared with estimates based on dominance proportions [37].

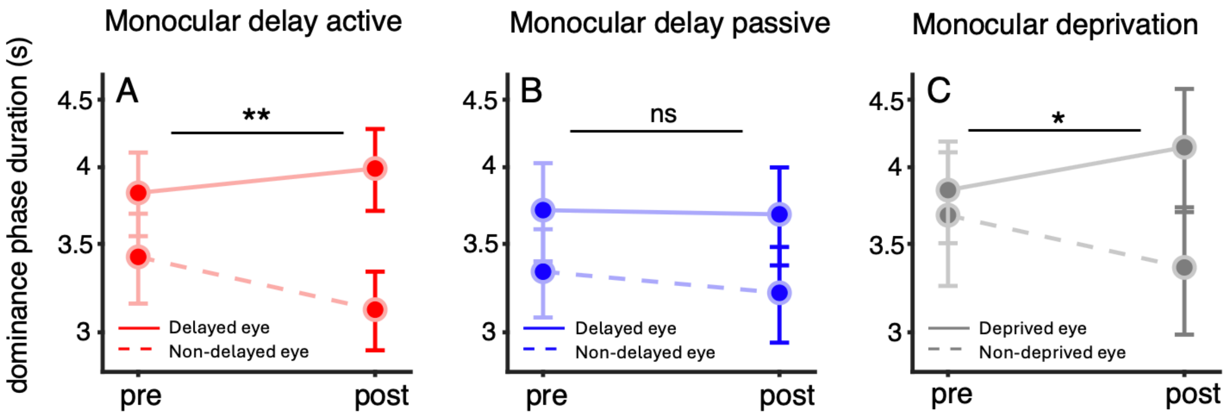

Figure 2-3 *Mean dominance phase durations for the two eyes, before and after each one-hour experimental condition: Continuous lines represent the manipulated eye (delayed or deprived), while dashed lines represent the non-manipulated eye. Error bars are standard errors across participants. Text insets report the significance of the interaction term of two-way ANOVAs with factors time (pre*

*vs. post) and eye (manipulated vs. non-manipulated) run separately in each condition – complete statistics are reported in the Supplementary Material; *p < 0.05; **p < 0.01; ***p < 0.001; ns non-significant.*

For completeness, we also checked the proportion of binocular rivalry mixed percepts, another important parameter of rivalry dynamics that represents the time during which neither eye completely dominates perception. We found no change in mixed percepts in either condition (see Supplementary Figure 2-5 and related text for statistics).

Using the more reliable proportion-based ocular dominance index (reported in Figure 2-2), we proceeded to analyze the relations between the ocular dominance shifts observed in the three conditions. Figure 2-4 shows individual participants' ΔOD% values, correlating the results for monocular delay during action (x-axes) with the results for the other two conditions. There was no correlation between the non-significant ocular dominance shifts induced by monocular delay during passive viewing and the significant shifts induced either by monocular delay during actions (robust correlation [38]: r(15) = 0.15, p = 0.608, logBF = -0.65, 1 outlier; Figure 2-4A) or by monocular deprivation (r(14) = -0.04, p = 0.898, logBF = -0.65, no outliers, *not shown*). In contrast, the effects of monocular delay during visually-guided goal-directed actions were significantly correlated with those of monocular deprivation (Figure 2-4B: r(15) = 0.61, p = 0.015, logBF = 0.56, no outliers); that the bisection line lays within the confidence interval of the robust linear fit confirms that the effects of the two conditions were statistically indistinguishable.

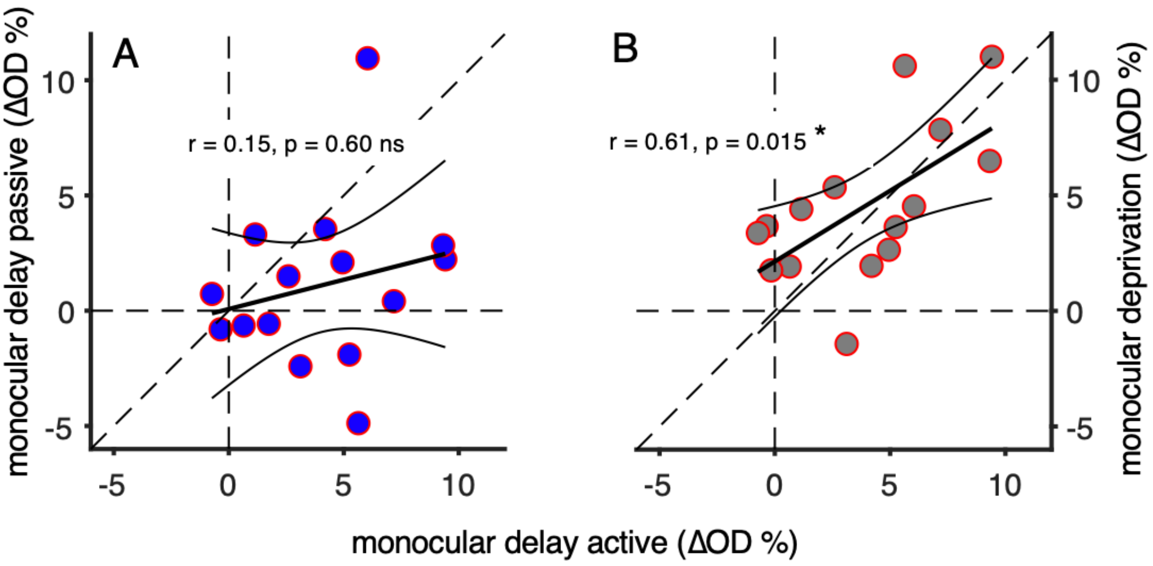

Figure 2-4 *Correlation between the ocular dominance shifts (ΔOD %, defined as the dominance of the manipulated eye measured after each one-hour experiment, minus the same value before the experiment) observed across the three experiments: A) Monocular delay during visually-guided goal-directed actions vs. passive viewing and B) Monocular delay during visually-guided goal-directed actions vs. monocular deprivation. Text insets report Pearson's correlation coefficients (r) and corresponding p-values, computed after automatic removal of the outliers with the robust regression toolbox*[38] *(*p<0.05, **p < 0.01, ns = not significant). Dashed black lines indicate the identity and zero functions. The continuous black lines show the best linear fit with confidence intervals.*

Our experimental design required that the active condition was always tested first, recording the videos to be replayed in the other two conditions; however, there are several indications that this did not confound our results. First, our experimental sessions were widely spaced (on average every two weeks), making it very unlikely that the short-lived ocular dominance shifts could have accumulated across sessions [39,40]. Second, we tested for variations in baseline ocular dominance across the three experiments and found no evidence for any habituation or familiarization effects (one-way ANOVA on preOD%: $F(2,26) = 1.03$, $p = 0.36$, $h_p^2 = 0.07$).

Discussion

Using an altered-reality system, we induced a temporal discrepancy between the visual input in the two eyes, while participants performed visually-guided goal-directed actions, or while they passively viewed a replay of their own actions with the same monocular delay. After one hour, ocular dominance shifted in favor of the delayed eye, but only if participants had actively engaged in the task, not when they had passively viewed the same visual scene. These results confirm and extend our previous observations [15], showing that monocular delay is sufficient to elicit short-term ocular dominance plasticity and that the effect is selectively observed during active task performance, not in passive viewing.

In passive viewing, monocular delay implies that the two eyes provide inconsistent but equally valid descriptions of the visual scene. Lacking strong temporal cues that adjudicate which eye is “online”, perception may sample from both eyes (perhaps in an alternating fashion), predicting no impact on ocular balance. In contrast, active task performance unambiguously flags the delayed eye as the one providing an invalid description of the visual scene. We suggest that this mismatch lays at the origin of the ocular dominance plasticity effect, promoting a boost of the mismatched eye representation. Multiple sources of action-related signals could be involved, including motor plans leading up to the actions, multisensory feedback from their execution and the accompanying attentional shifts.

Motor planning can influence perception through a corollary discharge mechanism [27-29]. In this model, the preparation of an action is characterized by the generation of two signals: a motor command, and a copy or corollary signal that is sent to the sensory systems to predict the consequences of the action. In this model, the corollary discharge signal serves to alert the sensory systems of the impending changes that will result from action execution, usually suppressing them from awareness [41]. In our paradigm, the corollary discharge can only predict the signals from the non-delayed eye, while the delayed eye could escape its suppressing effects. As a result, these mismatched signals may be transiently boosted [42] explaining the ocular dominance shift in favor of the delayed eye.

A similar mismatch occurs between signals from the delayed eye and the multisensory feedback from the actions. The execution of our tower-building task produced proprioceptive and tactile feedback signals linked with the manipulation of the wooden blocks, as well as auditory feedback signals, e.g. the sound of wooden blocks moved by the experimenter or falling on the desk. All these were out-of-synch with the visual changes in the delayed eye. In the present study, auditory cues were not included in the passive viewing condition, implying that we cannot evaluate their effect. However, in our previous study this mismatch was preserved in the passive condition, where participants watched and heard another person performing the tower-building task [15]. Nevertheless, no ocular dominance plasticity was observed. This suggests that audiovisual correspondence alone is not sufficient to flag the delayed eye as inconsistent. It remains an open question whether this is due to insufficient strength of the auditory cues or of multisensory integration [43]. An alternative possibility would be that motor signals related to the planning of goal-directed actions are a necessary component of the short-term plasticity effect, which cannot be reproduced by manipulating multisensory congruence alone. Follow-up studies are required to adjudicate between these competing interpretations.

There is evidence that watching a replay of one’s own actions in first-person perspective reactivates sensorimotor signals associated with the action plan [44,45]. According to an influential theory [30], the same network is activated when performing or imagining/observing an action, which may predict similar effects in our active and passive conditions (as long as observation triggered an internal simulation of the action). This could have predicted that passive viewing in first-person perspective elicited a similar ocular dominance shift as during actions, in contrast with the lack of effect with passive viewing in third-person perspective [15]. Instead, we find that the first- or third-person perspective produced comparable results: in both cases, passive viewing elicited no ocular dominance shift (note that first- and third-person perspective results are not directly comparable, as they were tested in different participants and under slightly different conditions, with auditory cues available in the third- not the first-person perspective case). This suggests that reactivating one's action schemes does not suffice to disambiguate which eye is mismatched and that plasticity is selectively elicited when monocular delay is combined with the execution of visually-guided goal-directed actions.

Actions are also tightly linked with the allocation of attention [46]. During goal-directed actions, attention tends to shift toward the action targets [47] and withdrawn from other locations [46]. As a result, attentional resources may be focused on visual changes seen by the online eye and withdrawn from those in the delayed eye. Can attention withdrawal explain the enhancement of the delayed eye after restoring normal vision? A recent series of studies [16,17] supported this view showing that directing attention to the movie-frames in one eye eventually shifted ocular dominance in favor of the unattended eye (which saw the same movie frames in reverse order). However, in those experiments the images in the two eyes were incompatible, disrupting binocular fusion like in most other monocular manipulations (monocular image distortion [20-22,24], inversion [19] or continuous suppression [25,48]). Under such conditions, directing attention to the image in one eye can promote interocular suppression of the other eye, essentially reproducing the effects of attenuating its input (deprivation), hence providing a possible explanation for its rebound boost. Contrary to most other monocular manipulations, ours (monocular delay) preserves the congruency between the two eyes at most visual locations, promoting binocular fusion. Mismatched signals primarily come from the hands and motor targets (only about 20% of the image); it is possible that allocation of action-linked attention to these targets is sufficient to trigger inter-ocular suppression and the rebound ocular dominance shift.

The effect of monocular delay during action had the same magnitude as the effect of monocular deprivation across our participants. This implies that mismatching visual signals at sparse locations in space time is sufficient to reproduce the effect of eliminating monocular visual information across most of the visual field. Thus, we conclude that short-term ocular dominance plasticity does not require manipulating the strength of visual input in the two eyes, or preventing binocular fusion, at least under conditions requiring visually-guided goal-directed actions.

Importantly, the correlation observed between the delay-induced and deprivation-induced ocular dominance shifts (Figure 2-4B) implies that participants who showed a strong effect in one condition tended to show a similarly strong effect in the other, indicating partially shared mechanisms. Future studies with larger samples will be necessary to formally characterize the stability and sources of this individual variability.

One apparent difference between monocular delay and monocular deprivation is their relation to action execution. While monocular delay selectively affected ocular dominance when combined with actions, monocular deprivation shifted ocular dominance even in our passive viewing condition. We suggest that this may be interpreted based on the different mismatch that monocular deprivation and monocular delay introduce relative to the multimodal context. While passive viewing eliminates the disadvantage of the delayed eye (both eyes provide an equally valid description of the visual field), the deprived eye may be flagged as inconsistent by its inability to provide any visual information. On this view, coherence with multimodal context could be seen as one of the mechanisms gating ocular dominance plasticity. This is in line with evidence suggesting that this form of plasticity engages multimodal factors [50,51]; it is also consistent with evidence that its effects extend beyond the primary visual cortex, where ocular dominance is set, encompassing a large-scale network reorganization [52].

Conclusion

We conclude that a small mismatch between monocular vision and the multimodal context is sufficient to elicit a short-term ocular dominance shift, reproducing the homeostatic plasticity elicited by monocular deprivation. Our results strengthen the evidence that performing visually-guided goal-directed actions gates this form of plasticity. This implies that multimodal signals (action plans and/or multisensory feedback and/or the accompanying attentional allocation) participate in setting the plasticity of sensory processing, even in adult individuals and even for features encoded at the earliest levels of the visual system – where the balance between monocular signals is set, likely in the primary visual cortex.

Supplementary data

Mean phase durations for each condition

In addition to the three-way ANOVA analysis run in our main text, we further quantified the change in mean phase duration dynamics separately for each condition (Figure 2-3 of the main text). As expected, the image in the dominant eye showed longer phases than the non-dominant eye at baseline (leftmost data-points in each panel of Figure 2). One hour of monocular delay during visually-guided goal-directed actions (Figure 2A) increased phase durations for the delayed eye and decreased those of the non-manipulated eye, implying an overall shift of ocular dominance in favor of the delayed eye. We evaluated the statistical significance of the effect with a two-way ANOVA for repeated measures, which revealed a significant interaction ($F(1,18) = 15.19$, $p = 0.001$, $\eta_p^2 = 0.46$) between factors eye (delayed vs. non-delayed) and time (before vs. after the 1h experiment). There was no main effect of time ($F(1,18) = 0.39$, $p = 0.53$, $\eta_p^2 = 0.02$), implying that this condition did not affect the two eyes in the same way; the significant main effect of eye ($F(1,18) = 31.51$, $p < 0.001$, $\eta_p^2 = 0.63$) indicates that the same eye remained dominant before and after the experiment. In contrast, no ocular dominance shift was observed when we replayed the videos recorded during the main experiment to a subset of the same participants, who watched them passively. Although visual stimulation was exactly the same as in the main experiment, with the same monocular delay, ocular dominance was unaffected (Figure 2B), with no significant eye by time interaction ($F(1,14) = 0.43$, $p = 0.52$, $\eta_p^2 = 0.03$), no significant main effect for factor time ($F(1,14) = 1.09$, $p = 0.31$, $\eta_p^2 = 0.07$) and only a main effect for the factor eye ($F(1,14) = 14.27$, $p = 0.002$, $\eta_p^2 = 0.50$), reflecting preserved ocular dominance before and after the experiment. When we replayed the same videos to a subset of participants, but replacing the delayed-eye image with a homogeneous gray screen (one hour of monocular deprivation), we observed the well-known ocular dominance shift in favor of the deprived eye (Figure 2C). The same two-way ANOVA used for the main experiment revealed a significant interaction (F(1,14) = 15.97, p = 0.001, $\eta_p^2 = 0.53$) between factors eye (deprived and non-deprived) and time (before vs. after the 1h experiment). There was no main effect of time (F(1,14) = 0.19, p = 0.66, $\eta_p^2 = 0.014$) and a significant effect of eye (F(1,14) = 9.22, p = 0.009, $\eta_p^2 = 0.39$), again indicating that the same eye remained dominant before and after the experiment.

Mixed percepts

Mixed percepts proportions do not change before and after monocular delay during visually-guided goal-directed actions (Figure 2-5A), while there is a non-significant trend for an increase of mixed percepts after the 1h experiments in the two passive stimulation conditions (monocular delay in passive viewing and monocular deprivation, Figure 2-5B-C). A two-way ANOVA for repeated measures on the subsample of participants tested with all three experiments (N=14), revealed no main effect of condition (F(2,26) = 0.273, p = 0.763, $\eta_p^2 = 0.021$) or interaction (F(2,26) = 0.491, p = 0.618 , $\eta_p^2 = 0.036$) but a significant main effect of the factor time (before and after the 1h experiments, F(1,13) = 5.97, p = 0.030, $\eta_p^2 = 0.315$). However, none of the post-hoc t-tests comparing the proportion of mixed percepts after vs. before each experiment was significant (all Bonferroni-corrected $p > 0.55$), indicative of a small effect that could only be revealed by pooling data across experiments.

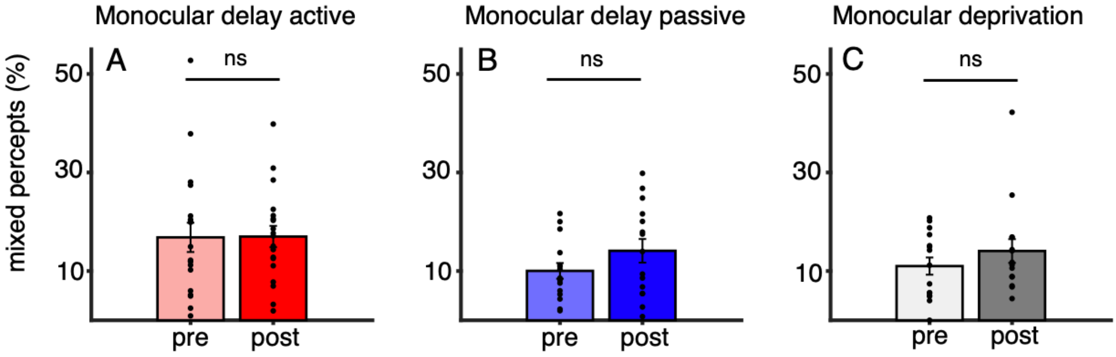

Figure 2-5 *Percentage of mixed percepts during binocular rivalry in each experimental condition. Bar plots show the mean and s.e.m. of mixed percepts (%) before (pre) and after (post) each 1-h experiment (black dots show individual participants' data): monocular delay during visually-guided goal-directed actions (A), monocular delay passive (B), and monocular deprivation (C). The top text symbols indicate the significance of the post-hoc t-tests evaluating the change pre vs. post (ns = not significant). The ANOVA and the post-hoc tests were run on the subset of N = 14 participants with data in all conditions, but the figure shows results from all participants.*

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CHAPTER 3:

The manuscript derived from this chapter is undergoing the process of peer-review; the text has been revised to reflect the comments received from the referees.

Prefatory Note
The present chapter reproduces the submitted manuscript with editorial adaptations to ensure coherence across the thesis. Introductory sections overlapping with earlier chapters have been condensed or replaced with cross-references to maintain continuity while preserving the integrity of the original article.

Visually guided voluntary actions boost short-term ocular dominance plasticity

Introduction

Short-term monocular deprivation reliably induces a transient shift of ocular dominance in favor of the deprived eye, as described in Chapter 1 [1-7]. Similar ocular dominance shifts can also been induced by manipulations that alter, rather than remove, monocular visual information – for example by distorting the image in one eye [8-12] or mismatching it with its multimodal context [13-18].

In Chapter 2 we provide direct support for this, showing that delaying the visual input in one eye induces an ocular dominance shift comparable to that produced by deprivation, but only when embedded within active visuomotor engagement; no effect emerged during passive viewing, despite identical visual input.

Here we asked whether the execution of voluntary, visually guided goal-directed manual actions would similarly modulate the effects of short-term monocular deprivation, resulting in a stronger ocular dominance shift when deprivation is combined with task execution compared with passive viewing.

A related question was addressed in previous studies, where participant's activity during the monocular deprivation was manipulated. Participants engaged in cognitive activities [25,13], simple motor learning [24], or physical exercise [19-23]. The results were highly heterogeneous, with some studies showing a large modulation of the deprivation effect, while others showed negligible or no differences. However, these studies generally did not match the visual input across conditions, leaving open the possibility that some of the action-related manipulations could have impacted plasticity via systematic changes in the visual stimulation.

Here we ensured that participants saw the same visual scene in two conditions: when they engaged in a tower-building task vs. when they passively viewed a replay of their own actions. We employed the same altered-reality setup described in Chapter 2 (without the monocular delay) and implemented a form of monocular deprivation by substituting the image in one eye with a gray screen. This design allowed us to isolate the impact of visually guided actions on the ocular dominance shift elicited by monocular deprivation.

Methods

Participants

We set sample size based on a prior study comparing ocular dominance plasticity across two conditions [18], where the effect size of the plasticity difference was indexed by a Cohen’s d = 0.9. Detecting such plasticity difference with 80% power and 5% error requires a minimum sample of N=12. We recruited 14 participants: of these, one failed to complete the second experimental condition, resulting in a final sample of 13 participants (9 females and 4 males), with age ranging between 20 and 31 years. All had normal or corrected-to-normal vision, no history of strabismus, amblyopia, or other binocular vision disorders, and no neurological or psychiatric conditions. Participants were naïve to the purpose of the experiment and provided written informed consent before participation. The study was approved by the local ethics committee [Comitato Etico Pediatrico Regionale - Azienda Ospedaliero-Universitaria Meyer - Firenze (FI); protocol "Plasticita' del Sistema visivo"] and conducted in accordance with the Declaration of Helsinki.

Experimental Setup

Our altered-reality set-up has been described in Chapter 2: here we summarize its main features. Participants sat at a desk, viewing the workspace (37 × 29 cm) and their own hands through an altered-reality system. Visual input was delivered via an Oculus Rift DK2 headset, which displayed stereoscopic images captured by a ZED stereo camera attached to the front of the headset (Figure 1). The system provided a visual field of approximately 80 × 60 degrees with a resolution of 960 × 720 pixels per eye. The refresh rates were 60 Hz for the headset display and 75 Hz for the camera. To accommodate individual differences in interpupillary distance, camera vergence was adjusted by modifying the horizontal offset between the images presented to the two eyes. The video stream was stored, resulting in first-person recordings of each participant's task performance; no audio was collected. Participants' heads were stabilized using a chinrest and headrest to which the headset assembly was fixed. In addition, an eye-tracking camera (Pupil Oculus DK2 eye-tracking add-on, Pupil Labs) positioned inside the headset continuously monitored the right eye at 120 Hz in both experimental conditions, allowing the experimenter to confirm that participants remained vigilant with their eyes open throughout the task. Eye-tracking signals for three participants were available for offline analyses.

Experimental Design

Each participant completed two experimental conditions, each lasting one hour and conducted on separate days (separated by a minimum of 1 week, and a median of 4 weeks), with binocular rivalry assessed at the beginning and the end. In addition, they participated in a preliminary session, where we collected binocular rivalry data (with the procedure described below) and used it to determine each participants' dominant eye.

In the first experimental condition, participants performed the tower-building task for one hour while the altered-reality system replaced the visual input to their dominant eye with a homogeneous gray screen (mean luminance: 5.85 cd/m2). A conceptually similar contrast-nulling paradigm has been used in previous studies [9,26,11,18]. The resulting monocular deprivation is bound to be less effective than monocular patching, given that residual contrast signals are delivered to the deprived eye - mainly, the edges of the display area, generating a sharp contrast between the gray screen and its dark frames. The non-deprived eye received the camera image in quasi-real time (about 35 ms delay), allowing participants to perform the task naturally. During the tower-building task, participants could hear the blocks falling and they interacted with the experimenter, e.g. when they encouraged participants to be fast and accurate in their task execution.

In the second experimental condition, participants viewed a first-person replay of their own actions recorded during the first condition, including the same gray screen in the deprived eye. Participants were instructed to passively watch the replay. As no audio was recorded in the first condition, participants could not hear the sounds related to their previous actions; however, they continued to interact with the experimenter throughout the experimental condition, ensuring that they remained vigilant and attentive.

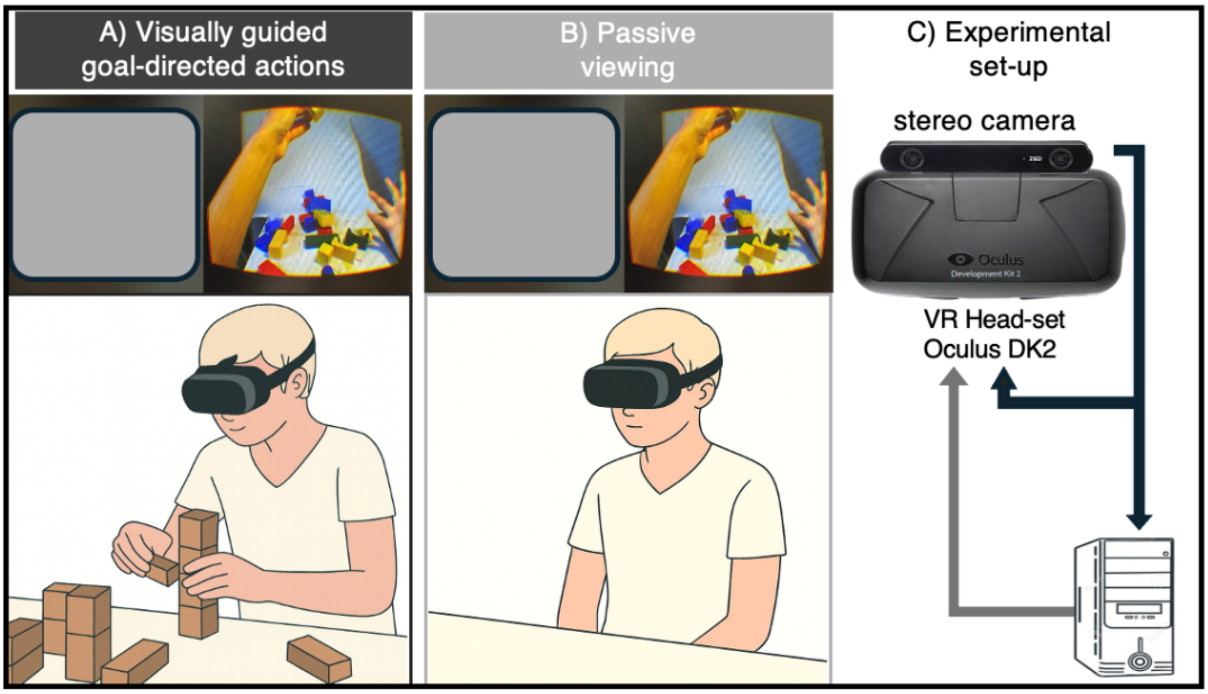

Figure 3-1 *Experimental set-up for the two experimental conditions. In the first condition (A), participants built towers with wooden blocks, monitoring their actions through an altered-reality set-up consisting of a stereo-camera mounted above an Oculus set; the image in their deprived eye was masked with a homogeneous grey screen. In the second condition (B), participants passively watched a replay of the visual input recorded in the first condition. Panel C shows schematically the flow of signals: captured by the stereo camera, sent back to the Oculus set and stored on disk to be replayed in the second condition. Each condition lasted 1 hour, immediately before and after it, binocular rivalry was used to assess ocular dominance.*

Ocular dominance assessment with binocular rivalry

Binocular rivalry was used to estimate ocular dominance before and after the 1 h of monocular deprivation using the same mirror stereoscope configuration described prevously [15,18]. Rivalry stimuli were orthogonal sinusoidal gratings (±45˚ orientation, spatial frequency: 2 cycles/deg spatial frequency), windowed by a Gaussian envelope ($\sigma = 2.5°$). A binocular presented fixation point and surrounding square frame facilitate stable fusion. Stimuli were displayed on a uniform background (mean luminance = 5.85 cd/m^2). Stimulus generation was implemented in MATLAB (MATLAB r2010a, The MathWorks) using Psycho-Toolbox [27-28] on a Mac computer. Images were shown on a gamma-corrected Display++ monitor (Cambridge Research Systems; 1920 x 1080 pixels, 120 Hz). Participants viewed the display at 57 cm with head stabilization via a chinrest.

Each rivalry block lasted 180 seconds. Participants continuously indicated perceptual state by pressing one of three keys corresponding clockwise dominance, counterclockwise dominance, or mixed percept (fusion or piecemeal). Four blocks (about 12 minutes) were collected before and after deprivation, with grating-eye assignments counterbalanced across blocks. Analyses focused on the first three blocks, where deprivation-induced effects are strongest [7].

Rivalry dynamics were quantified using mean phase durations (MPD) and dominance proportions. MPD corresponds to the average duration of exclusive perceptual dominance periods. Ocular dominance was indexed by the log-transformed ratio of mean phase duration between the deprived eye (DE) and non-deprived eye (NDE):

$$OD_{mpd} = \log10\left(\frac{DE_{mpd}}{NDE_{mpd}}\right) \qquad \text{(Equation 1)}$$

Dominance proportion represents the fraction total exclusive dominance time attributable to the deprived eye, calculated relative to the summed dominance duration of both eyes (excluding mixed percept intervals):

$$OD_{prop} = 100 * \frac{DE_{totaltime}}{DE_{totaltime}+NDE_{totaltime}} \qquad \text{(Equation 2)}$$

We also quantified the proportion of mixed percepts, a key parameter of binocular rivalry reflecting periods during which neither eye achieves complete perceptual dominance (e.g., binocular fusion or piecemeal perception).

These rivalry parameters were estimated four times: before and after each of the monocular deprivation conditions. We verified that the two pre-deprivation ocular dominance values were statistically indistinguishable (t(12) = 0.11, p = 0.911 and t(12) = 0.23, p = 0.816 for OD_{MPD} and OD_{PROP} respectively) and positively correlated (Pearson's r = 0.51, p = 0.077 and 0.65, p = 0.017), supporting the stability of our measurements across the two experimental conditions. We then proceeded to average pre-deprivation values to obtain a single baseline measure with reduced measurement error, against which we evaluated the effect of the two experimental conditions. This resulted in estimates of the ocular dominance shift following monocular deprivation during visually guided actions or in passive viewing, defined as the post-pre difference of the two OD_{MPD} and OD_{PROP} indices (ΔOD_{MPD} and ΔOD_{PROP}). The latter values could also be expressed as z-scores, with each participant's ΔOD divided by the standard deviation of their pre-deprivation OD, estimating the size of the OD shift after deprivation, relative to the physiological oscillation of OD values across experimental conditions.

All statistical analyses were performed using MATLAB [29] and JASP [30] (Team, 2024). A three-way repeated measures ANOVA was conducted to analyze the mean dominance duration of the deprived and non-deprived eyes, across experimental conditions, pre and post deprivation. Two-way repeated measures ANOVAs were conducted on binocular rivalry proportions of exclusive dominance and mixed percepts. The results of follow-up t-tests were Bonferroni corrected.

Results

Thirteen adult normally sighted individuals performed visually guided goal-directed actions (building towers with wooden blocks) in an altered-reality set-up, while the input to their deprived eye was replaced with a uniform gray screen, implementing a form of short-term monocular deprivation - although incomplete, given the residual contrast delivered to the deprived eye, e.g. at the edges of the display area, which shifted depending on eye movements. On a different day, the same participants watched a replay of their own actions in the same altered-reality set-up (with the same graying-out of the deprived eye). Participant were eye-tracked to verify that they remained vigilant and with both eyes open in all conditions; in a subset of three participants, we directly compared the number of frames where the eye-pupil was entirely visible, with no occlusion from the eye-lid, which averaged 91.8 ± 2.3% and 90.5 ± 1.6% (mean and s.e.m.), across visually-guided goal directed actions and passive viewing conditions; this implies small and comparable proportions of time during which the eye was blinking or closed. Before and after short-term monocular deprivation, we measured ocular dominance using binocular rivalry and observed a significant shift of ocular dominance in favor of the deprived eye.

Figure 3-2A-B shows mean dominance phase durations for both eyes, before and after each 1-h monocular deprivation. A repeated-measures ANOVA on log-transformed mean phase durations showed a significant three-way interaction ($F(1,12) = 9.66$, $p = 0.009$, $\eta p^2 = 0.45$) of factors *condition* (monocular deprivation during visually guided goal-directed actions or during passive watching) x *time* (before or after short-term monocular deprivation) x *eye* (dominant or non-dominant). This indicates that the effect of short-term monocular deprivation differed across conditions (see also below for a more direct evaluation of this difference). There was also a significant *eye* x *time* interaction ($F(1,12) = 36.02$, $p < 0.001$, $\eta p^2 = 0.75$) indicating a reliable shift of ocular dominance after the 1-h monocular deprivation. Given the significant interactions, the main effects are hard to interpret (for completeness: there was a significant main effect of *eye* ($F(1,12) = 40.67$, $p = 0.001$, $\eta p^2 = 0.77$), related to the longer dominance phases for the deprived (dominant) eye, a significant main effect of *time* ($F(1,12) = 7.24$, $p = 0.020$, $\eta p^2 = 0.38$), indicating that, on average, dominance phases were longer after deprivation, and a significant effect of *condition* x *eye*, indicating that phases for the deprived (dominant) eye were longer, on average, in the first condition ($F(1,12) = 6.25$, $p = 0.028$,

$\eta p^2 = 0.34$); no other main effects or interactions reached significance: *condition*: F(1,12) = 3.52, p = 0.085, $\eta p^2 = 0.23$; *condition* × *time*: F(1,12) = 1.70, p = 0.217, $\eta p^2 = 0.12$).

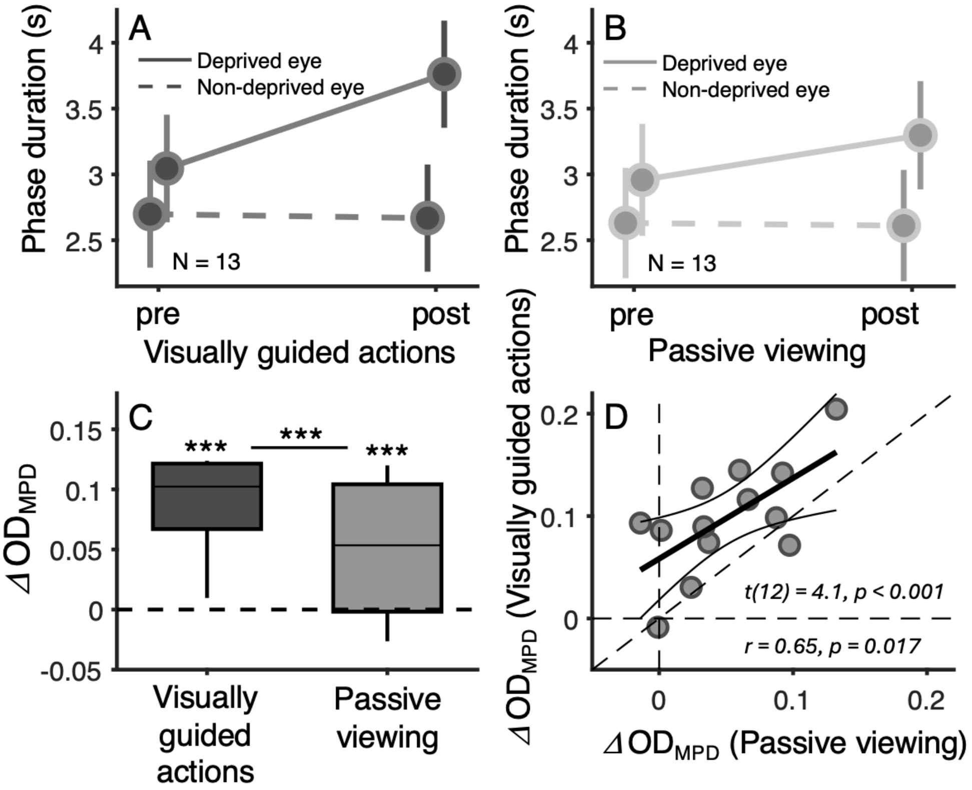

Figure 3-2 *Mean dominance phase durations for the two eyes, before and after each one-hour deprivation. A-B) Durations are expressed in seconds; values are plotted on a logarithmic scale. Continuous and dashed lines represent the deprived eye and non-deprived eye respectively. Error bars are standard errors across participants. C) Ocular dominance shifts in the two conditions, computed as post-deprivation values from each condition minus a baseline computed by averaging pre-deprivation values across conditions. The dashed line at y = 0 indicates no effect. Box plots show the median, interquartile and range of the distributions. Asterisks above each box plot indicate a significant shift of ocular dominance in each condition (significance evaluated after Bonferroni correction); the asterisks placed in-between the two box plots mark the significant difference between conditions (*p < 0.05, **p < 0.01, ***p < 0.001). D) Scatter plot of individual participants' ocular dominance shifts in the two conditions. Dashed black lines indicate the identity and zero functions.*

The continuous black lines show the best linear fit with confidence intervals. The text inset reports the Pearson's correlation of ocular dominance shifts in the two conditions with the corresponding p-values.

We used Equation 1 to extract an ocular dominance index from mean phase durations and directly compare the ocular dominance shift across the two experimental conditions. As the pre-deprivation values were well matched across conditions, we collapsed them into a single baseline value, to enhance the reliability of its comparison with the post-deprivation values. Figure 3-2C shows the resulting ocular dominance shift indices (post-pre deprivation difference). Both conditions showed a significant shift ($t(12) = 6.60$, $p < 0.001$; $t(12) = 4.10$, $p = 0.003$ for the visually guided actions and passive viewing conditions respectively; all p-values are Bonferroni corrected). Figure 3-2D shows that the effect was well correlated across conditions (Pearson's $r = 0.65$, $p = 0.017$); however, the ocular dominance shift was significantly larger when visually guided goal-directed actions were performed during short-term monocular deprivation, compared to passive viewing ($t(12) = 4.1$, $p < 0.001$), in line with the significant three-way interaction term of the ANOVA described above.

Similar conclusions were obtained by analyzing the other main rivalry parameter, dominance proportions (i.e., the proportion of time during which image presented in the deprived eye was perceived, relative to the total testing time with no fusion or mixed percepts, Equation 2 of the Methods). Figure 3-3A,B shows ocular dominance before and after each 1-h monocular deprivation. A two-way ANOVA revealed a significant main effect of *time* ($F(1,12) = 59.1$, $p < 0.001$, $\eta p^2 = 0.83$), and no main effect of *condition* ($F(1,12) = 2.49$, $p = 0.14$, $\eta p^2 = 0.17$). The *condition* x *time* interaction just missed significance ($F(1,12) = 4.53$, $p = 0.055$, $\eta p^2 = 0.27$). Figure 3-3C presents an alternative analysis, expressing the ocular dominance shift as the post-deprivation values in each condition, each subtracted of a combined pre-deprivation baseline (as done for mean phase duration in Figure 3-2C-D). This confirms that both experimental conditions showed a significant ocular dominance shift (t(12) = 6.87, p < 0.001; t(12) = 4.69, p = 0.001 for the visually guided actions and passive viewing conditions respectively, all p-values are Bonferroni corrected) and the effect was well correlated across conditions (Figure 3-3D, Pearson's r = 0.67, p = 0.018). In addition, the ocular dominance shift was significantly larger when visually guided goal-directed actions were performed during short-term monocular deprivation, compared to passive viewing (t(12) = 2.3, p = 0.044). Thus, the analyses of dominance proportions recapitulate the findings from mean phase durations, although with slightly reduced effect sizes.

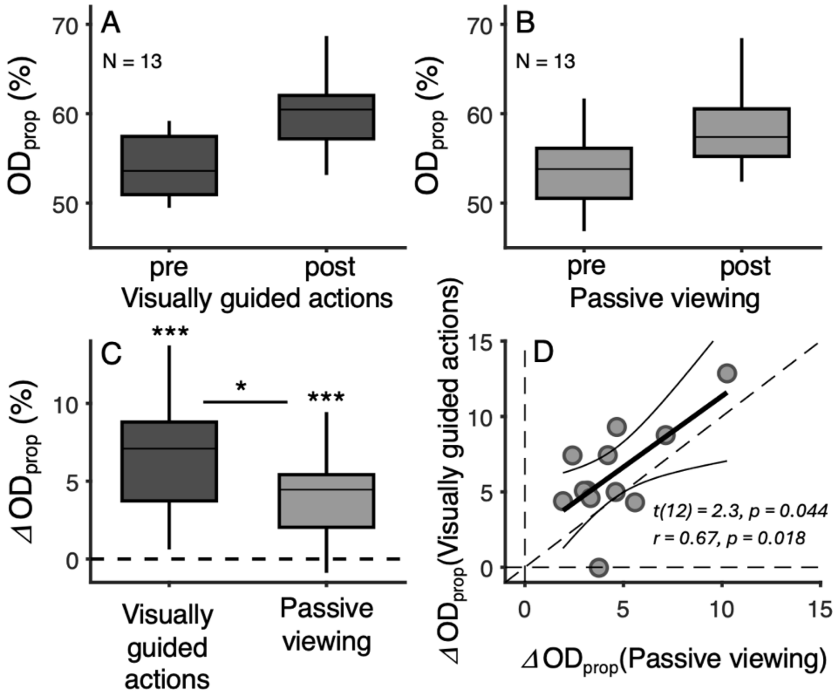

Figure 3-3 *Ocular dominance of deprived eye (A,B), before and after each one-hour monocular deprivation, during the execution of visually guided goal-directed action (dark grey) or in passive viewing (light grey). Proportions are expressed as percentages of dominance (see Equation 2). For both panels, box plots show the median, interquartile and range of the distributions. C) Ocular dominance shifts (post-deprivation values from each condition minus a common pre-deprivation baseline) elicited by short-term monocular deprivation in the two conditions. The dashed line at y =*

0 indicates no effect. Box plots show the median, interquartile and range of the distributions. Asterisks above each box plot indicate a significant shift of ocular dominance in each condition; the asterisk placed in-between the two box plots mark the significant difference between conditions ($*p < 0.05$, $**p < 0.01$, $***p < 0.001$*). D) Scatter plot of ocular dominance shifts in the two conditions (same values as in C). Dashed black lines indicate the identity and zero functions. The continuous black lines show the best linear fit with confidence intervals. The text inset reports the Pearson's correlation of ocular dominance shifts in the two conditions with the corresponding p-values.*

To quantify effect-sizes as estimated with both parameters, mean phase durations and dominance proportions, we divided the ocular dominance shifts observed in each condition by the standard deviation of the pre-deprivation ocular dominance, yielding a metric akin to a z-score. For ocular dominance indices based on mean phase durations, the average z-scores were 5.1 and 3.3 for monocular deprivation during visually guided goal-directed actions and passive viewing respectively; they were 6.3 and 4.5 for ocular dominance indices based on proportions. These values imply that, in the experimental conditions tested here, the ocular dominance change after monocular deprivation was more than 5-fold or 3-fold larger than the spontaneous variations of our indices across conditions.

Finally, we examined the proportion of mixed percepts during binocular rivalry (Figure 3-4). Analyses revealed no significant differences in mixed percept proportions before and after deprivation for either experimental condition: a two-way ANOVA showed no significant interaction between the factors *condition* and *time* ($F(1,12) < 0.04$, $p = 0.840$, $\eta p^2 < 0.01$), and no significant effects (*condition*: $F(1,12) = 1.08$, $p = 0.319$, $\eta p^2 = 0.08$; *time*: $F(1,12) = 0.01$, $p = 0.922$, $\eta p^2 < 0.001$). Comparing each post-deprivation value with the combined baseline confirmed no change of mixed proportion in either condition ($t(12) = 0.6$, $p = 0.536$ and $t(12) = 0.7$, $p = 0.498$ for the visually guided actions and passive viewing conditions respectively, with no significant difference between the two: $t(12) = 0.9$, $p = 0.408$).

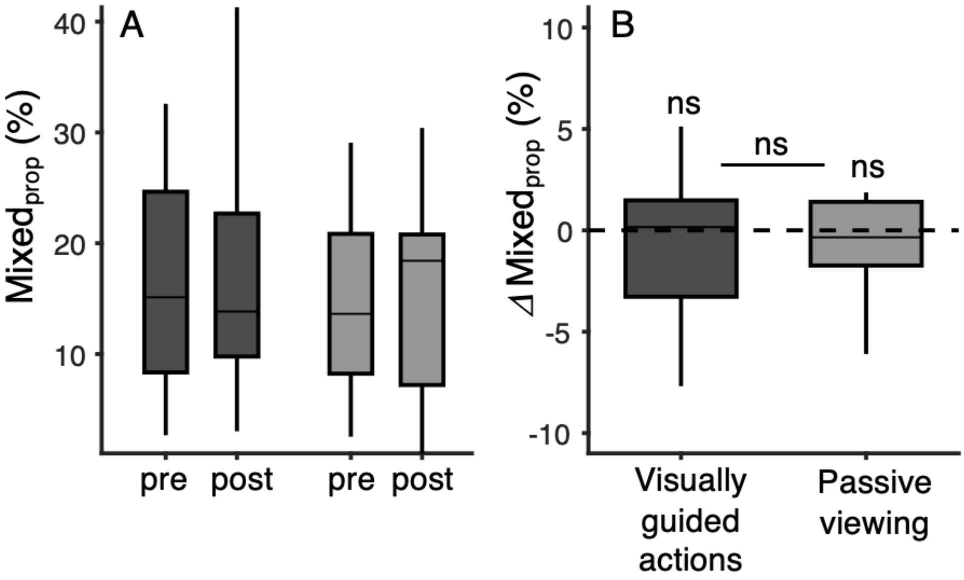

Figure 3-4 *Proportion of mixed percepts (A), before and after the one-hour monocular deprivation in the two experimental conditions. B) Post-deprivation values from each condition minus a common pre-deprivation baseline. The dashed line at y = 0 indicates no effect. For both panels, the box plots show the median, interquartile and range of the distributions. Text insets indicate the lack of any significant change of mixed percepts in both condition and the lack of significant differences across conditions (ns = non-significant).*

Discussion

We measured the effect of a one-hour monocular deprivation applied while participants performed visually guided goal-directed actions, or while they passively watched a recording of their own actions. In both conditions, we observed a significant shift of ocular dominance in favor of the deprived eye. The effect in our passive viewing condition was similar as in previous measurements obtained with the same setup in Chapter 2. The effect in the active condition was significantly larger, despite the closely matched visual input. This suggests that actions enhanced the effect of monocular deprivation – in line with our recent findings of actions gating the effect of monocular delay [15,18]. Note that all our participants completed the active condition first, and the passive viewing condition on a later day – a limitation intrinsic to our approach that could potentially create a temporal-order confounding effect. However, this is unlikely to explain our results, given previous evidence that the effects of short-term monocular deprivation do not build up or deteriorate with repetitions across days [19,20], similarly to contrast adaptation [21].

The effects of short-term monocular deprivation are usually interpreted as a form of homeostatic plasticity [5,7], where the reduced input to monocular neurons during deprivation rebounds into an upregulation of their gain, which persists for a short time after deprivation. This could be implemented by a local gain-control mechanism within the primary visual cortex V1, hosting monocular visual representations. That this effect is modulated by non-visual factors, like the execution of voluntary actions, implicates more complex circuitry extending beyond V1.

One possibility is that signals accompanying actions enhanced the non-deprived eye representation, either directly or via the inter-ocular inhibition circuitry [14], increasing the unbalance between eyes and thereby boosting the deprivation effect.

The non-deprived eye enhancement could be related to multisensory integration [22], as auditory signals (e.g., blocks slipping or falling on the table) accompanied actions and they were absent during passive replay – a limitation of our study. However, previous studies that manipulated the congruency between auditory signals and the stimulation in one eye found equivalent [15] or even reduced [14] short-term ocular dominance shifts.

Another source for the non-deprived eye enhancement could be attention, which tends to be allocated according to the goals of our actions [23]. A series of studies [14,16,17] showed that the selective allocation of attention to stimuli in one eye was sufficient to elicit a transient shift of ocular dominance in favor of the other eye, even without deprivation. When stimulation in one eye was deprived or reduced, attention could modulate the deprivation effect [13, 24, 25]. In principle, more focused attention during actions could explain the larger effect of deprivation compared to our passive viewing condition. However, since experiments with very different levels of attentional load (videogames requiring shoot [26] revealed comparable ocular dominance shifts [27], we deem this explanation unlikely. Still, a limitation of our study is that we did not directly monitor attention, implying that we cannot rule out an attentional contribution to our effects. Note that we did ensure that participants remained vigilant with their eyes open in both our conditions, during actions and in passive viewing, suggesting comparable "internal neural states" [28].

In the model outlined above, attention and/or multisensory integration would boost the non-deprived eye representation in our active condition compared to passive viewing. This implies a complex mechanism, where gain-control would follow a bi-phasic modulation: gradually shifting in one direction during the deprivation (enhancing the non-deprived eye) and suddenly swapping to the other direction at the end of the deprivation (suppressing the non-deprived eye to give the observed deprived eye dominance).

We recently put forward an alternative model [7], where we assume that the non-deprived eye is gradually suppressed throughout the deprivation, with a residual of this effect persisting at the end of the deprivation. What could be responsible for a suppression of the non-deprived eye, particularly during visually guided actions? Intriguingly, one such mechanism would derive from a classic model of vision during action: the corollary discharge or efference copy mechanism [29]. In this model, a copy or corollary of the motor command is sent to sensory regions, where it can predict and suppress the sensory consequences of actions. Thus, visual changes that are elicited by one's own actions are relatively suppressed. During monocular deprivation, visual changes that are elicited by one's own actions are selectively seen through the non-deprived eye, making it relatively suppressed. This model naturally fits in the theoretical framework of predictive coding [30, 31], whereby signals are relatively suppressed when they are consistent with their multimodal context, hence predictable; in contrast, unpredictable signals are relatively enhanced. It may seem counterintuitive to describe the impoverished experience in the deprived eye as unpredictable. However, a lifetime of binocular visual experience is likely to generate a strong expectation that both eyes convey structured visual input; covering one eye with a patch or nulling the contrast in its image inevitably mismatched this expectation. The unpredictability of the unstructured input in the deprived eye could explain its enhancement in passive viewing conditions (explaining the standard short-term monocular deprivation effect). We propose that performing visually guided actions would increase the predictability of the non-deprived eye, increasing the predictability difference across eyes and thereby enhancing the deprivation effect.

An implication of this account is that not all actions or activities modulate ocular dominance plasticity equally; this could help interpret the result from previous studies manipulating the task performed during the short-term deprivation. One study compared the effects of short-term monocular deprivation while participants actively played a video game or passively watched a pre-recorded session [26] and found no difference. Despite notable similarities between this study and ours, there are two key factors that could account for the divergent findings. First, Chen et al. [26] did not match visual images across conditions (the passive condition was not a replay of each participant's own game). Second, their visually guided actions were not manipulative actions affecting the participants' own surroundings, but merely keypresses moving figurines on a laptop computer or mobile device. That visually guided actions performed in this context failed to enhance short-term plasticity suggests that the quality of the actions and/or the richness of their visual consequences are important determinants of the effect. A similar reasoning could apply to the case of a motor learning task [32]. The learned manual actions happened outside the participants' field of view, i.e. they did not generate visual consequences; this could be the reason why they failed to enhance the ocular dominance plasticity. In fact, the ocular dominance plasticity was reduced in this condition compared to a baseline condition where participants were not tasked with specific instructions and could read/write/work at their laptops. We speculate that this could be linked with the impoverished visual input provided in the non-deprived eye during the motor learning task, which was limited to a repetitive set of digits (instructing the motor learning) implying that the non-deprived eye was less predictable than under normal circumstances.

Another case of impoverished visual input is presented in Wang et al. [13], specifically in a passive condition where the non-deprived eye was exposed to a nearly uniform background (and the deprived eye was covered with an opaque patch and therefor exposed to total dark). No ocular dominance shift was observed. This was contrasted with a second condition, where participant did a jigsaw puzzle during the two-hour deprivation and a reliable ocular dominance shift was observed. Clearly, the visual input in the two conditions was incomparable. We propose that the lack of deprivation effect observed in their passive condition is due to both eyes being equally unpredictable (both mismatching the prediction that eyes convey structured visual input), hence equally enhanced. A logically opposite scenario was explored in our recent studies [15,18], where neither eye was deprived of visual input, but one eye was merely delayed in time. In passive viewing conditions, there was no shift of ocular dominance, which we interpret by assuming that both eyes were equally predictable, both providing an equally valid description of the visual field. In contrast, a reliable ocular dominance shift was obtained during visually guided actions, which unequivocally flagged the delayed eye as unpredictable, boosting its dominance [15,18]. Taken together, these results imply that depriving the input in one eye is neither sufficient [13] nor necessary [15,18] to induce short-term ocular dominance plasticity, and the short-term plasticity effect depends critically on the behavioral context where the monocular manipulation was applied.

One final set of related experiments asked participants to engage in physical exercise during short-term deprivation [33-38]. These were inspired by evidence that physical activity enhances cortical excitability and plasticity in animal models [39,40]. While Lunghi & Sale [33] reported a reliable boost of plasticity with physical exercise, the other studies did not reveal this modulation. Importantly, these paradigms differ from ours in several respects. First, the goal-directed manual actions required in our task certainly required a very different level of physical activity (e.g. effort, fatigue, etc.) than cycling on a stationary bike, as required in most of the studies on physical exercise. Second, contrary to our paradigm and the other manipulations mentioned above, the cycling task was not strongly dependent on visual guidance. Third, ours and the other visually guided tasks generally produced reliable and systematic visual changes, e.g. the motion produced by the movement of the participant's own hands. This was not necessarily the case during physical exercise. Still, we note that cycling on a stationary bike could induce more head movements, and potentially more visual changes, than sitting still in front of a screen. Our results suggest that such visual changes linked with actions could modulate the short-term deprivation effect and potentially help explain the discrepant results across some of these studies.

Conclusions

Our results indicate that the task performed during short-term monocular deprivation is an important factor for determining the ocular dominance plasticity effect. This aligns with previous evidence for the importance of action in short-term ocular dominance plasticity. We suggest that the impact of actions on short-term plasticity depends on the generation of visual changes that are consistent with action plans. This fits in a predictive coding account of short-term plasticity, whereby transiently depriving one eye of visual input makes it less predictable, hence boosts its dominance compared to a more predictable non-deprived eye, particularly when the latter visual input is consistent with action plans.

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GENERAL DISCUSSION

This thesis addressed a central question: what mechanisms underlie short-term ocular dominance plasticity in the adult visual system, and what does this phenomenon reveal about residual plasticity beyond developmental critical periods?

Chapter 1 provided a quantitative synthesis of 73 studies on short-term monocular deprivation, demonstrating that the ocular dominance shift is a robust and replicable phenomenon across measurement techniques and experimental designs. Importantly, the meta-analysis revealed that qualitatively similar effects can also be elicited by manipulations that do not reduce visual input but instead alter its coherence, temporal structure, or behavioral relevance. This observation broadened the interpretative framework of short-term plasticity, suggesting that reduced sensory drive may not be the sole trigger of the effect.

Chapter 2 experimentally tested this possibility by dissociating deprivation from interocular mismatch. We showed that delaying the visual input in one eye during active visuomotor coordination is sufficient to induce an ocular dominance shift comparable in magnitude to that produced by classical monocular deprivation. Crucially, this effect was contingent upon active engagement: passive exposure to the same delayed stimulation did not produce measurable plasticity. These findings highlighted the importance of behavioral context and suggested that plasticity mechanisms are gated by sensorimotor contingencies.

Chapter 3 extended this line of investigation by asking whether active engagement similarly modulates the classical monocular deprivation effect. We found that monocular deprivation reliably induced plasticity even during passive viewing, but that the effect was significantly enhanced when participants performed visually guided goal-directed actions during the deprivation period.

Taken together, the three chapters converge on a central conclusion: short-term ocular dominance plasticity in adulthood is not a purely stimulus-driven phenomenon. Instead, it reflects a flexible, context-sensitive mechanism whose magnitude depends on the relationship between sensory input, behavioral engagement, and multimodal predictions.

Short-term monocular deprivation has traditionally been interpreted within a homeostatic plasticity framework. According to this view, transient reductions in sensory input trigger compensatory adjustments in synaptic efficacy, thereby stabilizing neural activity levels. The paradoxical boost of the deprived eye following brief deprivation has been taken as evidence of such rapid homeostatic upregulation.

The results presented in this thesis are broadly consistent this interpretation. In both experimental studies, a reliable ocular dominance shift in favor of the deprived or manipulated eye was observed. Moreover, the meta-analysis confirmed that the effect is robust across experimental paradigms, and that its magnitude scales with deprivation duration—consistent with a dose-dependent compensatory mechanism.

At the same time, the present findings suggests that homeostatic framework alone may not fully capture the range of conditions under which short-term ocular dominance plasticity emerges. Comparable ocular dominance shifts can be achieved without nulling the visual input strength, e.g. through monocular delay (as shown here) or through monocular image distortion [1] and inversion [2]. Furthermore, the enhancement of deprivation effects during visually guided goal-directed actions [3], indicates that the attenuation of input in one eye is neither necessary nor sufficient to elicit the ocular dominance shift. These observations point to a critical role of behavioral and multi-modal context in shaping plasticity.

A central contribution of this thesis lies in demonstrating that behavioral context systematically modulates short-term ocular dominance plasticity. Across Chapters 2 and 3, active visuomotor engagement emerged as a critical factor influencing the magnitude of the plastic response.

In the case of monocular delay, active engagement was necessary to induce plasticity. Passive exposure to identical visual input was insufficient. In contrast, classical monocular deprivation produced plasticity even during passive viewing, yet the effect was significantly enhanced during visually guided actions. These dissociations suggest that behavioral engagement acts as a gating factor rather than as a simple additive enhancer.

Visually guided actions generate structured sensorimotor contingencies. They produce predictable visual consequences, multisensory feedback, and shifts of endogenous attention toward action goals. Under these conditions, the visual input from the non-manipulated eye becomes tightly coupled to action outcomes, potentially increasing its functional reliability. Conversely, mismatches—whether temporal delays or absence of expected input—may become more salient. Short-term ocular dominance plasticity thus appears to depend not only on input strength, but on how sensory relate to ongoing behavior and expectation.

The convergence of these findings invites a theoretical interpretation that extends beyond classical homeostasis. Rather than replacing the homeostatic account we propose that it may be complemented by a predictive framework.

The predictive coding framework rests on a Bayesian inference model in which the brain continuously generates and updates predictions about the incoming sensory information [4,5]. These predictions, generated in high-level cognitive and pre-motor areas, are projected to lower-level sensory areas in the form of top-down modulatory signals. Low-level sensory areas compare these predictions with the bottom-up sensory drive, e.g. the thalamic visual input to V1. The key assumption of "predictive coding" models is that a substantial fraction of neural activity in these low-level sensory areas represents the discrepancy between bottom-up and top-down signals. In other words, rather than representing the sensory input, low-level sensory areas would selectively represent unpredictable events.

From this perspective, the ocular dominance shifts elicited by monocular deprivation and other types of monocular manipulations may emerge in response to a sustained violation of expectation. A lifetime of binocular vision establishes a strong expectation that both eyes should convey structured visual input. Depriving one eye mismatches this expectation, and this might explain the enhanced cortical representation of the deprived (unpredictable) eye and its increased dominance.

Importantly, deprivation is not the only way to make one eye unpredictable. Interfering with visual information in one eye without changing the strength of the visual input – like monocular delay (our work) and monocular inversions [2] or distortions [1] – should make it similarly unpredictable. In the monocular delay experiment, for example, the input from the manipulated (delayed) eye is inconsistent with the visually guided goal-directed actions. As a result, the delayed eye is marked as unpredictable and consequently strengthened. However, when no actions are performed, the two eyes provide equally valid descriptions of the visual field; neither of them is systematically less predictable than the other (in a sense, both are unpredictable to a degree) resulting in no net enhancement of either eye and no ocular dominance shift.

In this integrative view, short-term ocular dominance plasticity reflects the interaction between activity-dependent stabilization mechanisms and context-sensitive prediction error minimization.

In conclusion, we outlined a general framework of the characteristics and traits of short-term ocular dominance plasticity; however, many aspects of this phenomenon require further investigation and the hypotheses on its underlying mechanisms (including ours) remain essentially speculative.

From a broader theoretical perspective, ocular dominance plasticity provides a privileged model for studying how the adult brain adapts to a constantly changing sensory input. The translational implications of this line of research are considerable. Identifying the factors that trigger and modulate plasticity in the adult visual system may inform the development of more effective intervention strategies for functional recovery across a wide range of clinical conditions.

Amblyopia represents the most direct example. Short-term monocular deprivation protocols have already been explored as tools to transiently shift ocular dominance in favor of the amblyopic eye, potentially creating a window of enhanced receptivity for perceptual training. However, reassigning cortical function could promote recovery in many other disorders – an outcome that has so far remained elusive in primary sensory and motor areas, long considered resistant to plastic change in adulthood.

Ultimately, the present findings support a view of adult plasticity as inherently context-dependent: the adult brain retains a capacity for rapid functional reorganization, contingent on specific constellations of sensory and behavioral conditions. Defining those conditions more precisely represents a central challenge for future research.

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