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Multisensory Research

Plasticity, and its Limits, in Adult Human Primary Visual Cortex

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Abstract:	There is an ongoing debate about whether adult human primary visual cortex (V1) is capable of large-scale cortical reorganization in response to bilateral retinal lesions. Animal models suggest that the visual neural circuitry maintains some plasticity through adulthood, and there are also a few human imaging studies in support this notion. However, the interpretation of these data has been brought into question, because there are factors besides cortical reorganization that could also explain the results. Still, how reasonable would it be to accept that adult human V1 does not reorganize itself in the face of disease? Here, we discuss new evidence for the hypothesis that adult human V1 is not as capable of reorganization as in animals and juveniles, because in adult humans, cortical reorganization would come with costs that outweigh its benefits. These costs are likely functional and visible in recent experiments on adaptation—a rapid, short-term form of neural plasticity—where they prevent reorganization from being sustained over the long-term.				
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Plasticity, and its Limits, in Adult Human Primary Visual Cortex

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Abstract

There is an ongoing debate about whether adult human primary visual cortex (V1) is capable of large-scale cortical reorganization in response to bilateral retinal lesions. Animal models suggest that the visual neural circuitry maintains some plasticity through adulthood, and there are also a few human imaging studies in support this notion. However, the interpretation of these data has been brought into question, because there are factors besides cortical reorganization that could also explain the results. Still, how reasonable would it be to accept that adult human V1 does not reorganize itself in the face of disease? Here, we discuss new evidence for the hypothesis that adult human V1 is not as capable of reorganization as in animals and juveniles, because in adult humans, cortical reorganization would come with costs that outweigh its benefits. These costs are likely functional and visible in recent experiments on adaptation—a rapid, short-term form of neural plasticity—where they prevent reorganization from being sustained over the long-term.

Keywords

Neuroplasticity, Primary Visual Cortex, Human Adults, Costs

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4 If the retina is damaged in both eyes, primary visual cortex (V1) no longer receives
5 input. It is widely hypothesized that neurons within the V1 cortical lesion
6 projection zone (LPZ) respond to the absence of incoming information by shifting
7 their receptive fields from the blind toward intact portions of the visual field (as
8 suggested by e.g., Kaas et al., 1990; Gilbert and Wiesel, 1992; Darian-Smith and
9 Gilbert, 1994; Chino et al., 1992; Chino et al., 1995; Calford et al., 1999; Calford
10 et al., 2000; Schmid et al., 1995; Darian-Smith and Gilbert, 1995). This type of
11 visual brain plasticity is often called ‘remapping’, because the relocation of
12 neuronal receptive fields will change V1’s retinotopic map: retinotopic maps in
13 cortex emerge from the fact that nearby visual neurons have receptive fields at
14 nearby locations in the visual field, so when neurons shift the location of their
15 receptive fields, the retinotopic map will change accordingly. Visual brain
16 plasticity in the form of remapping is generally thought to be slow, because it
17 would require that structural changes are made to the underlying neural circuitry.
18 However, recently, the interpretation of the data presented in support of cortical
19 remapping has been seriously questioned (see Wandell and Smirnakis, 2009 for a
20 review).

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42 Another important type of visual brain plasticity is neuronal adaptation. In contrast
43 to cortical remapping, neuronal adaptation is generally very fast (e.g., Clifford et
44 al., 2000; Kohn, 2007; Wandell and Smirnakis, 2009). For instance, if a person
45 looks at a waterfall for a short period of time and then shifts her gaze away, the
46 world will perceptually move upward (Anstis et al., 1998). This motion after-effect
47 is thought to be due to the fact that motion-processing visual neurons adjust their
48 responsiveness, which likely reflects an attempt to optimize visual processing by
49 maintaining a state of equal time-averaged activity and decorrelated neuronal
50 stimulus sensitivity (Attneave, 1954; Andrews, 1964, Ullman and Schechtman,
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4 1982; Barlow and Fołdiák, 1989; Anstis et al., 1998; Wainwright, 1999; Benucci
5 et al., 2013; Haak et al., 2014a). Unlike the neuronal receptive field changes
6 underlying cortical remapping, the changes underlying neural adaptation do not
7 appear to rely on structural changes in the visual neural circuitry (Clifford et al.,
8 2000; Kohn, 2007; Wandell and Smirnakis, 2009), but rather on functional
9 interactions, such as mutual inhibition (Movshon and Lennie, 1979; Barlow and
10 Fołdiák, 1989).

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20 Whereas neuronal adaptation is a firmly established property of the visual system
21 across species and ages (Clifford et al., 2000; Kohn, 2007), cortical remapping
22 following retinal lesions has yet to receive such status, particularly in adult humans
23 (for a review, see Wandell and Smirnakis, 2009). A handful of functional magnetic
24 resonance imaging (fMRI) studies have characterized abnormal functional
25 magnetic resonance imaging (fMRI) activity in V1 following retinal lesions (e.g.,
26 Baker et al., 2005; Schumacher et al., 2008; Baker et al., 2008; Dilks et al., 2009;
27 Dilks et al., 2014), thereby claiming evidence of large-scale reorganization.
28 However, abnormal activity in itself does not warrant the conclusion that cortical
29 remapping has occurred (Masuda et al., 2008; Wandell and Smirnakis, 2009;
30 Baseler et al., 2009; Masuda et al., 2010; Haak et al., 2014c). Cortical remapping
31 can only be concluded on the basis of abnormal activity patterns if it can also be
32 shown that the absence of visual input in itself does not change the measurements
33 in the same way. For instance, in a recent study, Baseler et al. (2011) compared the
34 fMRI activity patterns from the cortical lesion projection zone (LPZ) in macular
35 degeneration patients with real retinal lesions and healthy controls with simulated
36 retinal lesions. They found that although the LPZ in V1 was largely silenced by
37 both real and simulated retinal lesions, for a small fraction of voxels (~5%) the
38 patients with real retinal lesions exhibited the same apparent neuronal receptive
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4 field changes as controls with simulated lesions, indicating that these changes were
5 caused by the absence of visual stimulation alone. Importantly, these voxels were
6 found far into the LPZ, indicating that the receptive field changes could not be
7 easily explained by measurement artifacts at the fringe of the LPZ (Haak et al.,
8 2012; Binda et al., 2013). Rather, they appeared to be a feature of visual cortical
9 processing, unveiled in the absence of visual stimulation.
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12 In the first instance, it seems quite reasonable to expect that the adult human brain
13 would adjust itself in the face of retinal lesions. After all, if children are capable of
14 developing relatively normal vision even when an entire occipital lobe failed to
15 develop (e.g., Werth, 2006, Muckli et al., 2009, but see Haak et al., 2014c), one
16 might also expect the brain to at least ameliorate the consequences of a retinal
17 lesion by dedicating the now-redundant resources of deafferented cortex to
18 processing retinal inputs that are still intact. The net effect of such cortical
19 remapping would be quite similar to the perceptual ‘filling-in’ of the blind-spot of
20 the healthy retina, as well as the perceptual filling-in that occurs when someone
21 stares steadily at an image with patches of missing ‘texture’ for a prolonged period
22 of time (Ramachandran and Gregory, 1991; Pettet and Gilbert, 1992; Komatsu,
23 2006; Weil and Rees, 2011). Here, the patches of missing ‘image data’ will be
24 perceptually filled-in with the texture from surrounding image regions. Just like the
25 after-effects of neuronal adaptation, perceptual filling-in occurs fairly rapidly, and
26 the neural mechanisms underlying perceptual filling-in could likewise be
27 interpreted as a way of optimizing visual processing in the context of the preceding
28 stimulus history (i.e., in the vein of Horace Barlow’s redundancy reduction
29 hypothesis; c.f. Barlow, 1961; Barlow, 2001). Thus, perceptual filling-in, which
30 would be the consequence of cortical remapping in response to retinal lesions if it
31 occurred, seems to share important features with visual neuroplasticity in the form
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4 of neuronal adaptation. Therefore, as the loss of vision endures, it might be
5 expected that the brain would eventually change its neural circuitry via cortical
6 remapping to sustain perceptual filling-in over the long-term. However, this does
7 not appear to be the case—perceptual filling-in does not appear to produce long-
8 term, hard-wired changes in the face of a retinal lesion.
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16 Interestingly, recent work now suggests that neuronal adaptation may also not
17 produce hard-wired changes over the long-term. Using immersive virtual reality,
18 Haak et al. (2014b) exposed a group of young adults to a world with only very
19 little vertical visual contrast energy for four days continuously, in an attempt to
20 mimic classic selective rearing experiments (Hirsch and Spinelli, 1970; Blakemore
21 and Cooper, 1970) in adult humans. Just as staring at a waterfall for a prolonged
22 period of time changes the response gains of motion-sensitive neurons, the
23 prolonged viewing of a world with relatively little vertical contrast will cause
24 adjustments to the responsiveness of orientation-selective cells in primary visual
25 cortex (e.g., Graham, 1989; Maffei et al., 1973; Movshon and Lennie, 1973;
26 Ohzawa et al., 1985; Dragoi et al., 2000). Monitoring for the perceptual
27 consequences of these changes in the responsiveness of orientation-selective
28 neurons, Haak et al. (2014b) found that adaptation increased in magnitude during
29 the first day, but then decreased, despite the sustained presence of the adapting
30 environment. Thus, it appears that there are factors that prevent visual
31 neuroplasticity, in the form of neuronal adaptation, from being sustained over the
32 long-term.
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53 Haak et al. (2014b) concluded that if neuronal adaptation does in fact optimize
54 vision, then the decline in adaptation strength must be due to costs that outweighed
55 its benefits. An obvious candidate cost is the ‘coding catastrophe’, where changes
56 in the firing of neurons responsible for early visual processing are mistaken for
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4 stimulus-changes by neurons that are responsible for subsequent, higher-level
5 stages of visual processing (Schwartz et al., 2007; Series et al., 2009; Druv and
6 Carandini, 2014; Patterson et al., 2014). Indeed, when Patterson et al. (2014)
7 induced adaptive changes in the responsiveness of V1 neurons in the macaque by
8 having them stare at a drifting grating pattern for some time, this impeded the
9 ability of neurons in area MT, which receives most of its inputs from V1, to
10 integrate the V1 signals into a plaid pattern. They concluded that “the effects of
11 adaptation cascade through the visual system, derailing the downstream
12 representation of distinct stimulus attributes”.

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24 Importantly, the decline in adaptation strength observed by Haak et al. (2014b) was
25 then followed by an increase in adaptation during subsequent days, indicating that
26 a second, more slowly acting adaptive mechanism was able to overcome the costs
27 of the initial adjustments in neuronal responsiveness. It is likely that this second,
28 slower form of adaptation reflects a process more similar to ‘perceptual learning’,
29 during which the visual system typically adjusts the neural codes in later rather
30 than in earlier visual areas (see e.g., Hochstein and Ahissar, 2002; Ahissar and
31 Hochstein, 2004). This would make sense, because later stages of visual processing
32 are typically concerned with more abstract sensory representations that require
33 more flexible neural codes. Moreover, compared with the areas responsible for the
34 early stages of visual processing, there are far fewer downstream areas that depend
35 on the information throughput of later visual areas. Thus, by shifting the adaptive
36 neural code adjustments from the early to higher-level visual areas, the brain may
37 be able to optimize vision without the adverse effects of the coding catastrophe.
38 Indeed, Haak et al. (2014b) observed that the tilt-aftereffect, an illusion thought to
39 be due to the coding-catastrophe, began to decline toward the end of the
40 experiment.

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4 Here, we put forward the hypothesis that the same principles may also apply to
5 visual processing in the face of retinal lesions. That is, the retinal lesion would
6 initially cause rapid ‘adaptive’ changes in the location of the receptive fields of the
7 neurons within the lesion projection zone in V1. These changes, however, will
8 likely cause havoc at later stages of vision, due to the mismatch between the
9 assumed and true stimulus locations that their afferents encode. Thus, early stage
10 changes could soon be undone, as perceptual filling-in is postponed to later stages
11 of visual processing (in line with e.g. De Weerd et al., 1995; Murakami et al., 1997;
12 Cornelissen et al., 2006). A cost-induced shift of cortical reorganization from
13 earlier to later stages of visual processing would straightforwardly explain why
14 reorganization in the form of cortical remapping appears to be absent in adult V1
15 (Sunness et al., 2004; Smirnakis et al., 2005; Wandell and Smirnakis, 2009;
16 Baseler et al., 2011). The hypothesis is also consistent with the task-dependent
17 differences in V1 activation between patients and controls reported by Masuda et
18 al. (2008, 2010), who reasoned that the task-dependent responses in the LPZ of V1
19 must reflect unmasked feedback signals from the extra-striate visual areas, rather
20 than cortical reorganization at the level of V1.
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41 As there are many controversies surrounding the claims of cortical remapping in
42 cats, primates and humans (see Wandell and Smirnakis, 2009), perhaps the most
43 convincing evidence of cortical remapping in adult V1 comes from studies in mice
44 (e.g., Keck et al., 2008). Why would the coding catastrophe not limit cortical
45 remapping in adult mice with binocular retinal lesions? One reason could be that
46 mice do not rely as much on vision as cats, primates and humans do (mice are
47 nocturnal and navigate using mainly their nose and whiskers), and so the costs of
48 cortical remapping may be lower for them. Another reason could be that V1 is in
49 fact a relatively high-level area within the mouse visual hierarchy, such that it
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4 serves relatively late-stage rather than early-stage visual processing. If so, fewer
5 visual processing stages would be adversely affected by plastic changes in V1. In a
6 similar vein, the costs of cortical remapping may be lower in mice if mouse V1
7 were to feed its information straight to the areas with highly flexible processing
8 capabilities (see e.g., Wang and Burkhalter, 2007), thereby bypassing mid-level
9 processing stages (corresponding to e.g. human visual area V2) that are more
10 constrained in the variety of their inputs. Regardless, there is no doubt that visual
11 cortex in mice is very different from visual cortex in (human) primates, with
12 mouse visual cortex containing for instance no orientation columns, and many
13 fewer extrastriate visual areas (Baker, 2013; Huberman and Niell, 2011), leaving
14 open the possibility that it contains different mechanisms of plasticity.
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29 Claims of cortical remapping have not been limited to visual cortex. In auditory
30 cortex, for instance, ‘filling-in’ like changes have been observed in the topographic
31 cortical representation of sound frequency (i.e., auditory cortex’ tonotopic map)
32 starting weeks after localized lesions were applied to the cochlea of the inner ear
33 (e.g., Robertson and Irvine, 1989). Though the criticisms of cortical remapping in
34 the visual domain may also apply to auditory cortex, it is interesting to note that
35 primary auditory cortex (A1) is a relatively later stage within the auditory
36 processing pathways than V1 is within the visual processing hierarchy. That is,
37 there are many more subcortical stops before auditory information reaches cortex
38 than there are stops leading up to V1, and there are many fewer high-level cortical
39 auditory areas than there are high-level visual areas beyond V1. Indeed, it has been
40 proposed that A1 represents stimuli in a highly task-dependent fashion, thereby
41 affording a relatively high amount of learning-induced plasticity (e.g., Ohl and
42 Scheich, 2005; Polley et al., 2006). Thus, the difference in the degree of cortical
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4 reorganization in A1 and V1 appears to fit well with the idea that the brain prefers
5 to make plastic changes at the later stages of sensory processing.
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10 In conclusion, there appears to be converging evidence to suggest that adult human
11 primary visual cortex is not very susceptible to cortical remapping. Here, we have
12 put forward the hypothesis that this could be due to the costs associated with
13 making changes at the very root of the visual processing hierarchy. It would make
14 more sense for the visual system to make long-term structural adjustments at later
15 stages of visual processing, because the later stages have fewer dependencies that
16 may be adversely affected (Hochstein and Ahissar, 2002; Ahissar and Hochstein,
17 2004). This principle may not only apply to brain plasticity in the form of cortical
18 remapping in response to bilateral retinal lesions, but also when it comes to various
19 multimodal forms of cortical reorganization.
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